The Large Synoptic Survey Telescope

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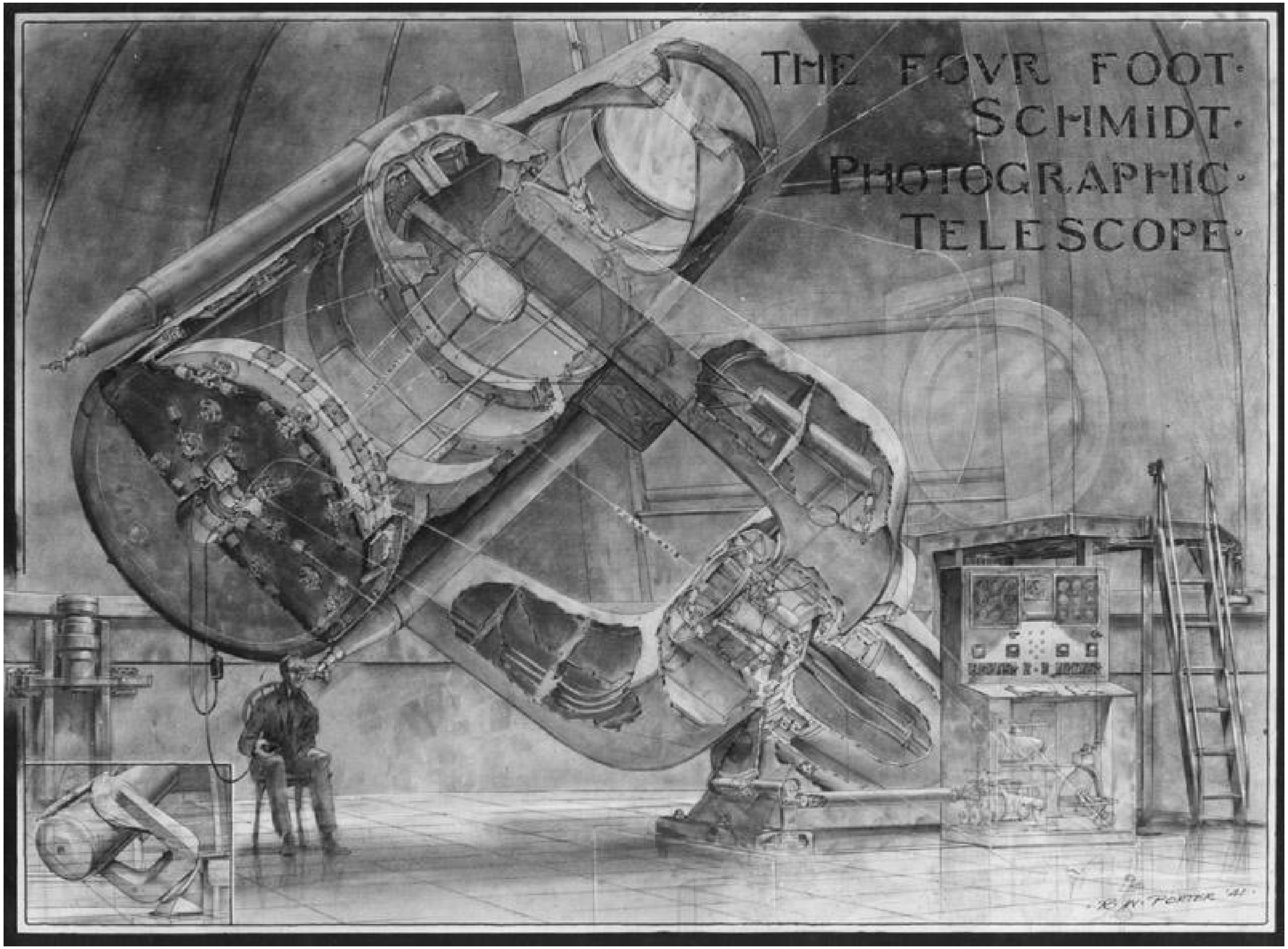
What is the LSST?

- The LSST will be a large, wide-field ground-based telescope designed to provide time-lapse digital imaging of faint astronomical objects across the entire visible sky every few nights.

- LSST will enable a wide variety of complementary scientific investigations, utilizing a common database. These range from searches for small bodies in the solar system to precision astrometry of the outer regions of the galaxy to systematic monitoring for transient phenomena in the optical sky.

- Of particular interest for cosmology and fundamental physics, LSST will provide strong constraints on models of dark matter and dark energy through statistical studies of the shapes and distributions of faint galaxies at moderate to high redshift.

Wide-Field Imaging is Not New…



However, LSST will go *Wide, Deep, and Fast:*

- The solid angle surveyed per unit time, to some limiting flux, *F,* at a signal-to-noise ratio, *SNR*, in exposures of time, *t*, is given by:

$$\frac{d\Omega}{dt} = F^2 \frac{A\Omega\varepsilon}{SNR^2}\left[\Phi_{sky}\delta\Omega + \alpha_{\det}/t\right]$$

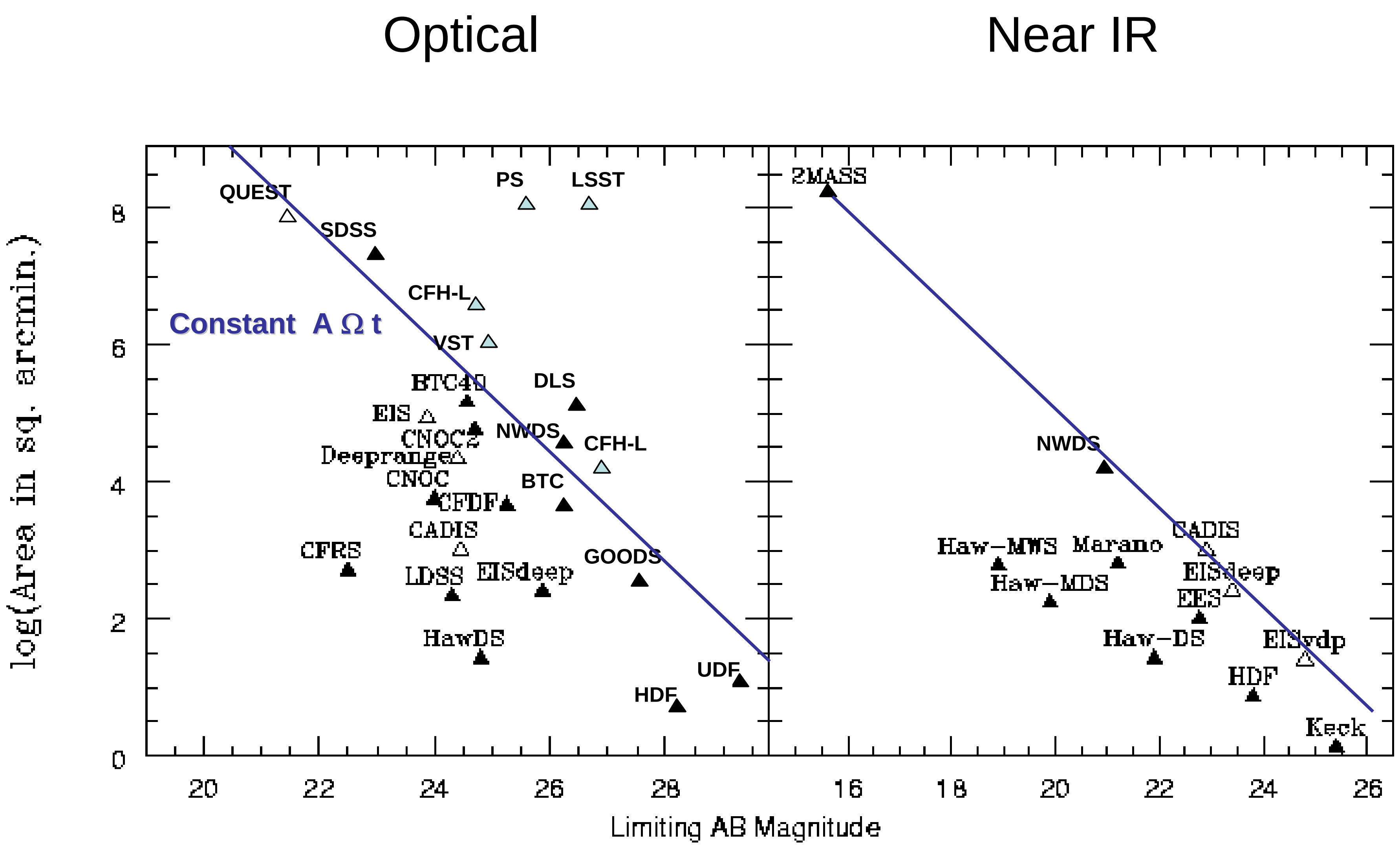
Here $A\Omega$ is the étendue of the telescope, ε is the efficiency of the system, Φ_{sky} is the sky intensity, $\delta\Omega$ is the size of the seeing-limited PSF, and $\alpha_{\det}$ is proportional to detector noise and trap depth.

- Large surveys require high étendue. But with conventional optical designs - high étendue requires large detector area.

- An experiment like LSST has only become possible now because of the relatively recent development of large format CCD arrays!

Some Recent Optical and Near IR Surveys

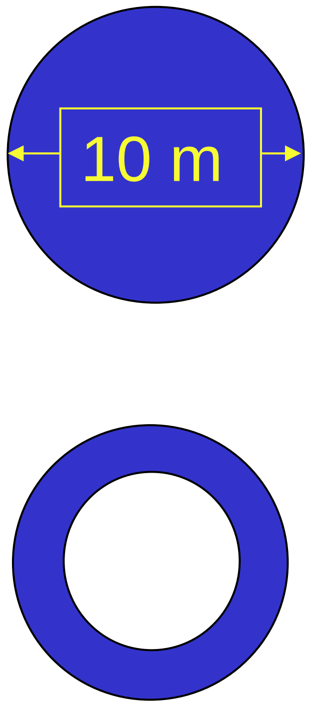
Large Synoptic Survey Telescope



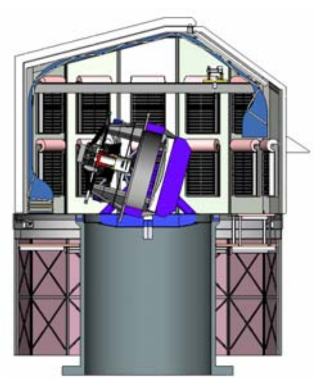
Comparison of LSST To Keck

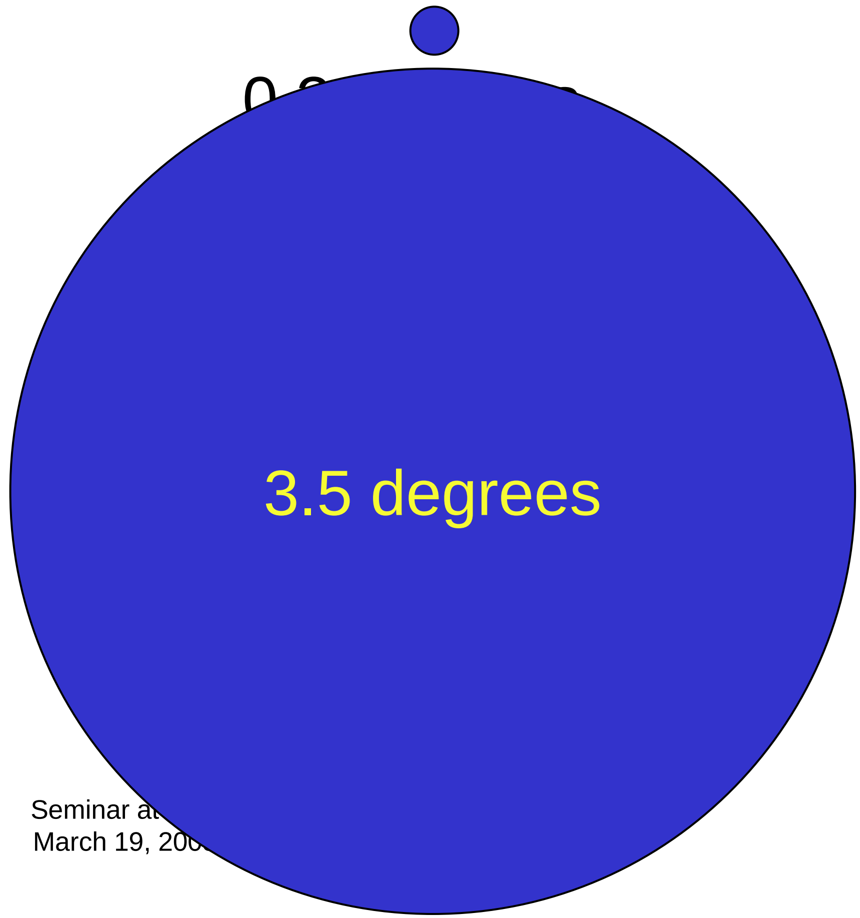
Primary mirror diameter

Field of view
(full moon is 0.5 degrees)



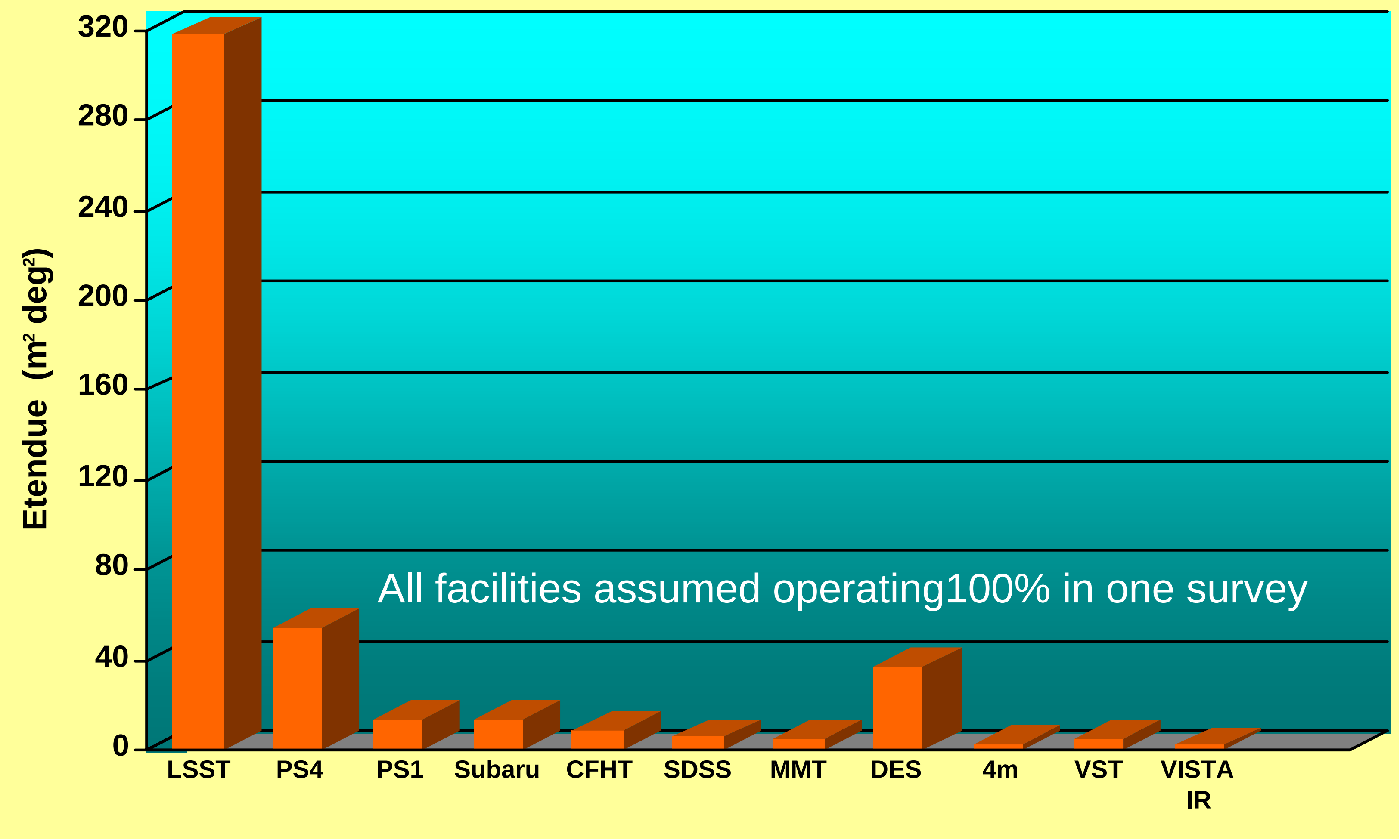
Keck Telescope





LSST

Relative Etendue (= AΩ)



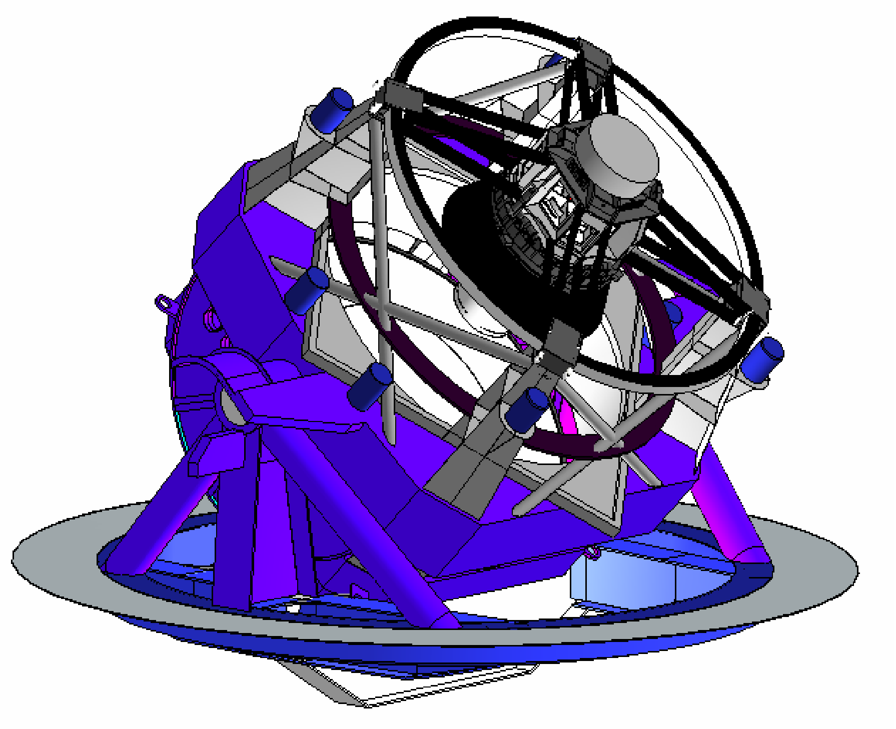
Large Synoptic Survey Telescope

History:

The need for a facility to survey the sky *Wide, Fast and Deep*, has been recognized for many years.

1996-2000 "*Dark Matter Telescope*"
Emphasized mapping dark matter

2000- "*LSST*"
Emphasized a broad range of science from the same multi-wavelength survey data



LSST Ranked High Priority By US Review Committees

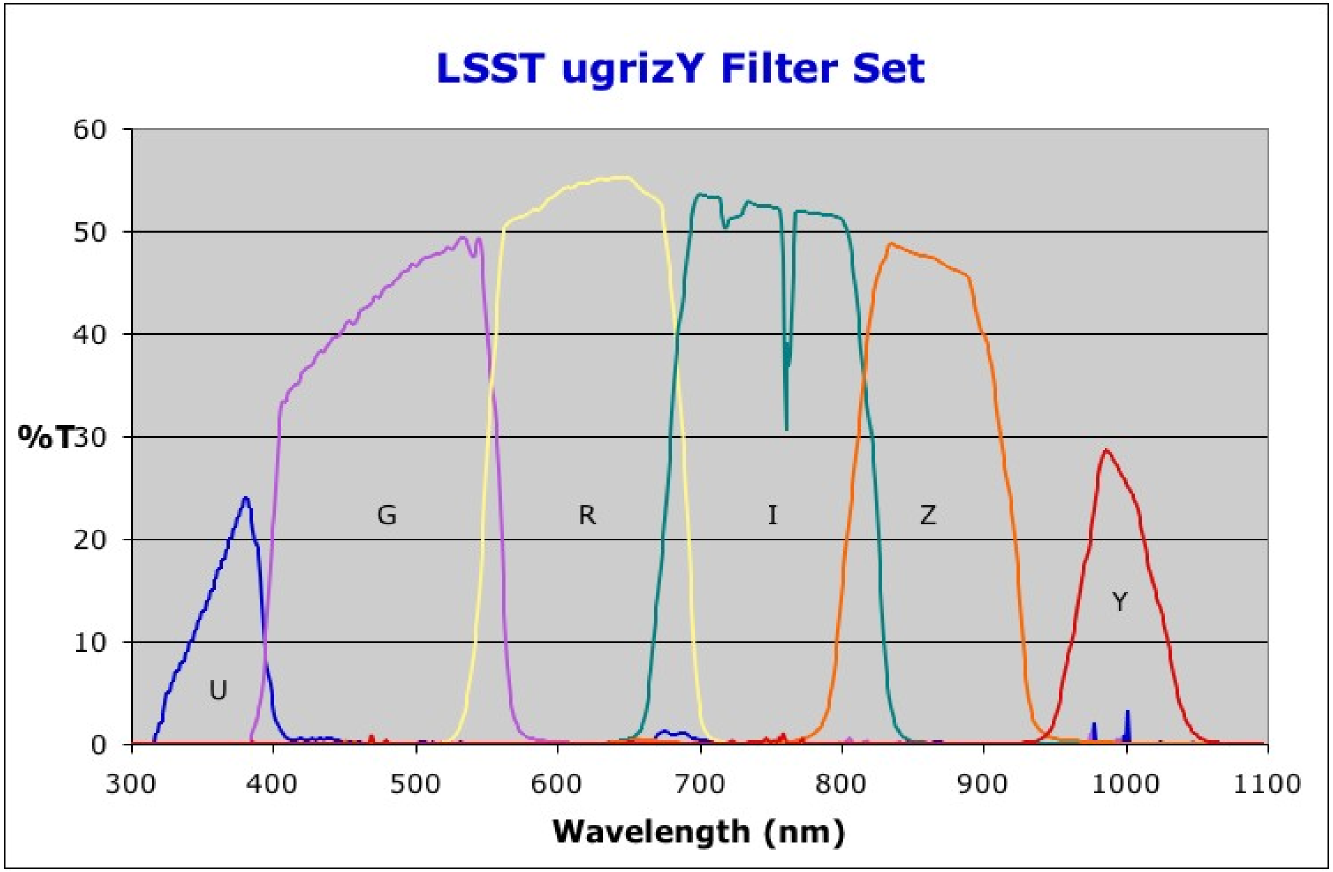
- NRC Astronomy Decadal Survey (AANM)
- NRC New Frontiers in the Solar System
- NRC Quarks-to-Cosmos
- Quantum Universe
- Physics of the Universe
- SAGENAP
- NSF OIR 2005-2010 Long Range Plan
- Dark Energy Task Force
- P5 Report - Summer 2006

LSST Survey

- 6-band Survey: *ugrizy* 320–1050 nm
- Frequent revisits: 2 x 15 s, 25 AB mag/visit
- Sky area covered: > 20,000 deg^2, 0.2 arcsec / pixel
- Each 10 sq.deg FOV revisited ~2000 times
- 10-Year Duration: Yields 27.7 AB magnitude @ 5σ
- Photometric precision: 0.01 mag reqt, 0.001 mag goal

LSST Filter Set and System Throughput

Large Synoptic Survey Telescope



Massively Parallel Astrophysics

- Dark matter/dark energy via weak lensing
- Dark matter/dark energy via baryon acoustic oscillations
- Dark energy via supernovae
- Dark energy via counts of clusters of galaxies
- Galactic Structure encompassing local group
- Dense astrometry over 20000 sq.deg: rare moving objects
- Gamma Ray Bursts and transients to high redshift
- Gravitational micro-lensing
- Strong galaxy & cluster lensing: physics of dark matter
- Multi-image lensed SN time delays: separate test of cosmology
- Variable stars/galaxies: black hole accretion
- QSO time delays vs z: independent test of dark energy
- Optical bursters to 25 mag: the unknown
- 5-band 27 mag photometric survey: unprecedented volume
- Solar System Probes: Earth-crossing asteroids, Comets, trans- Neptunian objects

LSST and Dark Energy

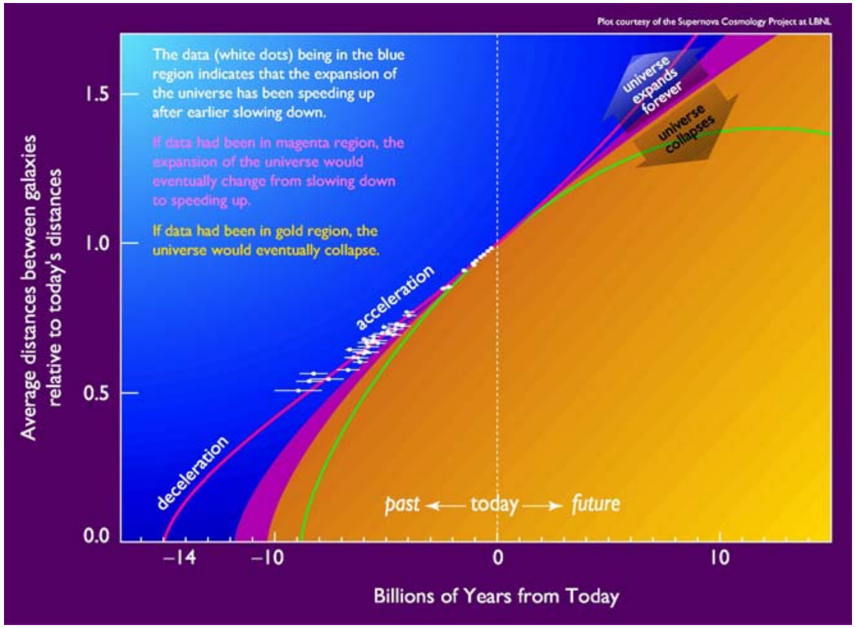
Large Synoptic Survey Telescope

- The acceleration of the cosmic expansion for a homogeneous and isotropic universe is given by the equation:

$$\frac{\ddot{a}}{a} = \frac{-4\pi G}{3}(\rho + 3P) + \frac{\Lambda}{3}$$

- For a NR gas, P ~ 0. For radiation, P = ρ/3. In both cases, the universe should be decelerating if there is no cosmological constant.

- Positive acceleration can occur for a non-zero value of Λ, or for an energy field with negative pressure. The so-called equation of state parameter: $w = P/\rho$, must be < -1/3.



LSST and Dark Energy

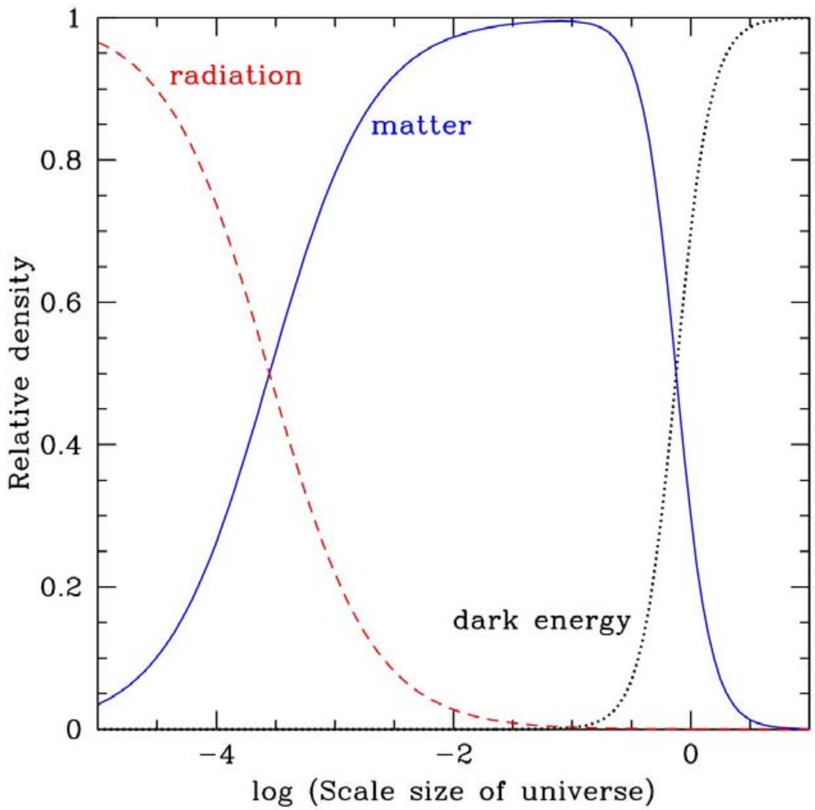
- The existence of dark energy poses a major problem for modern theoretical physics.

- Quantum field theory predicts a cosmological constant due to vacuum modes, unless the expansion is truncated at some mass scale. Truncation at the Planck scale yields a value of Λ 120 orders of magnitude larger than observed. Truncation at the TeV scale only reduces the problem by 60 orders magnitude.

- Supersymmetry can eliminate the cosmological constant, since fermion modes cancel boson modes. But it is difficult to get a small but non-zero value of Λ from such theories. The relevant mass scale for the observed value of Λ is in the meV range. We thought we understood physics in that energy range!

LSST and Dark Energy

- Especially puzzling is the "why now" problem.
- The energy density in radiation drops like a^{-4}. The energy density in matter drops like a^{-3}. The energy density in Λ is constant.
- It is incredibly unlikely that we should be living in an era when the energy density in matter is comparable to that in dark energy.
- This suggests that although the standard ΛCDM cosmological model works very well, there must be some new physics lurking behind it!



LSST and Dark Energy

- The only observational handle that we have for understanding the properties of dark energy is the expansion history of the universe itself. This is parametrized by the Hubble parameter:

$$H(z) = \frac{\dot{a}}{a}$$

- Cosmic distances are proportional to integrals of $H(z)^{-1}$ over redshift. We can constrain $H(z)$ by measuring luminosity distances of standard candles (Type 1a SNe), or angular diameter distances of standard rulers (baryon acoustic oscillations).

- Another powerful approach involves measuring the growth of structure as a function of redshift. Stars, galaxies, clusters of galaxies grow by gravitational instability as the universe cools. This provides a kind of cosmic "clock" - the redshift at which structures of a given mass start to form is very sensitive to the expansion history.

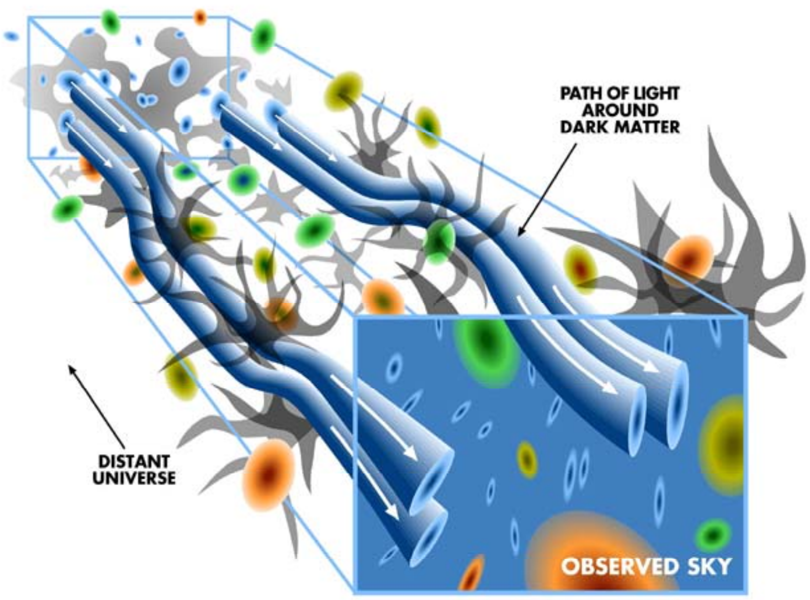
LSST Probes Dark Energy in Multiple Ways

- Cosmic shear (growth of structure + cosmic geometry)
- Counts of massive structures vs redshift (growth of structure)
- Baryon acoustic oscillations (angular diameter distance)
- Measurements of Type 1a SNe (luminosity distance)
- Mass power spectrum on very large scales tests CDM paradigm
- Shortest scales of dark matter clumping tests models of dark matter particle physics

The LSST survey will address all with a single dataset!

Cosmic Shear

- The term "cosmic shear" refers to the systematic and correlated distortion of the appearance of background galaxies due to weak gravitational lensing by the clustering of dark matter in the intervening universe.
- As light from background galaxies passes through the intergalactic medium, it gets deflected by gravitational potentials associated with intervening structures. A given galaxy image is both displaced and sheared.
- The effect is detectable only statistically. The shearing of neighboring galaxies is correlated, because their light follows similar paths on the way to earth.



LSST and Cosmic Shear

Large Synoptic Survey Telescope

- The simplest measure of cosmic shear is the 2-pt correlation function measured with respect to angular scale.

- This is usually plotted as a power spectrum as a function of multipole moment (similar to the CMB temperature maps).

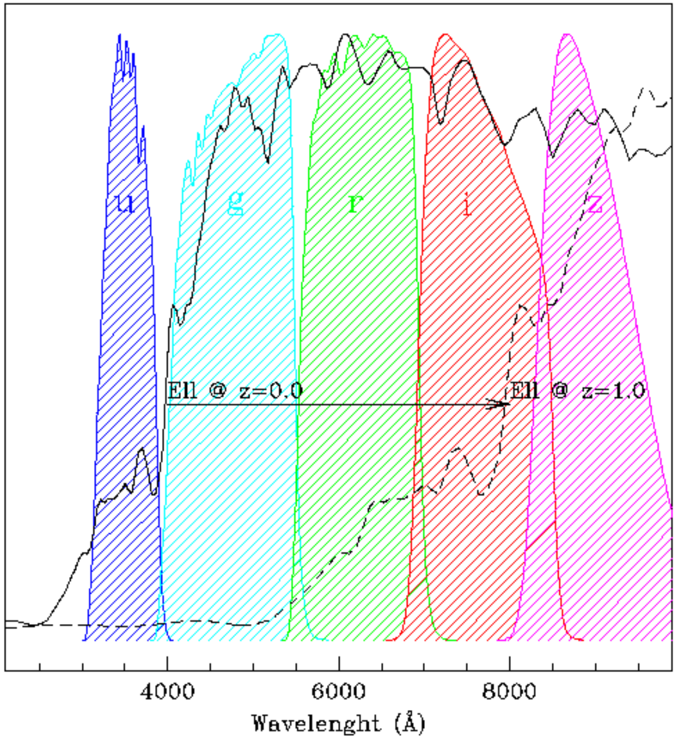
- Note the points of inflection in these curves. This is a transition from the linear to the non-linear regime.

- The growth in the shear power spectrum with the redshift of the background galaxies is very sensitive to *H(z)*. This provides the constraints on dark energy.

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

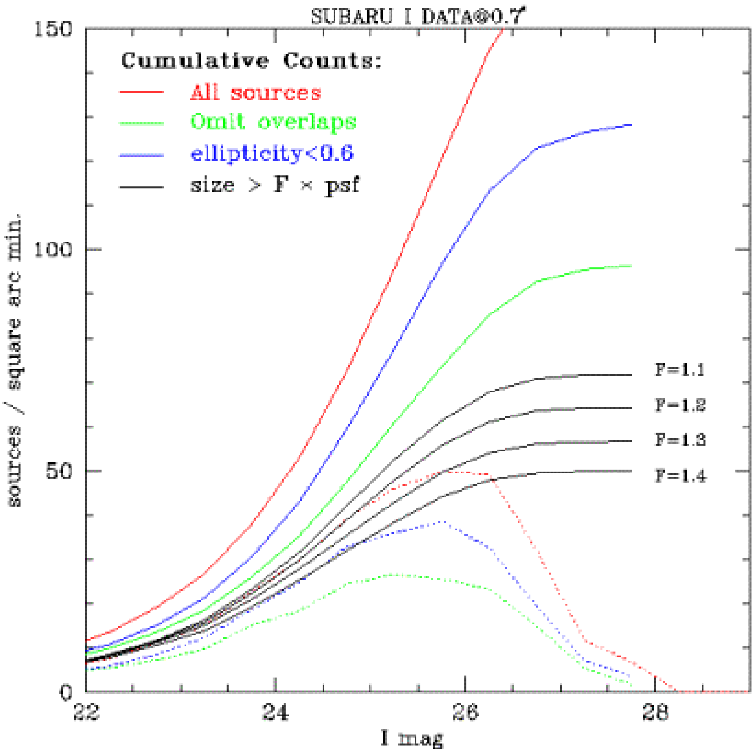
Photometric Redshifts

- Galaxies have distinct spectra, with characteristic features at known rest wavelengths.
- Accurate redshifts can be obtained by taking spectra of each galaxy. But this is impractical for the billions of galaxies we will use for LSST cosmic shear studies.
- Instead, we use the colors of the galaxies obtained from the images themselves. This requires accurate calibration of both the photometry and of the intrinsic galaxy spectra as a function of redshift.



LSST is Optimally Sized for Measurements of Cosmic Shear

- On small scales, the shear error is dominated by shape noise - it scales like the sqrt of the number of galaxies per squ. arcmin.
- On larger scales, cosmic variance dominates - it scales like the sqrt of the total solid angle of sky covered.
- From the ground, the number of galaxies per squ. arcmin levels off at mag 26.5.
- With the LSST etendue, this depth can be achieved over the entire visible sky.



Cosmic Shear - Dealing with Systematics

- The cosmic shear signal on larger angular scales is at a very low level.

- To make this measurement, we must be confident that we understand and can remove spurious sources of shear. These can arise in the atmosphere or in the optics of the telescope and camera.

- LSST is the first large telescope designed with weak lensing in mind. Nevertheless, it is essentially impossible to build a telescope with no asymmetries in the point spread function (PSF) at the level we require.

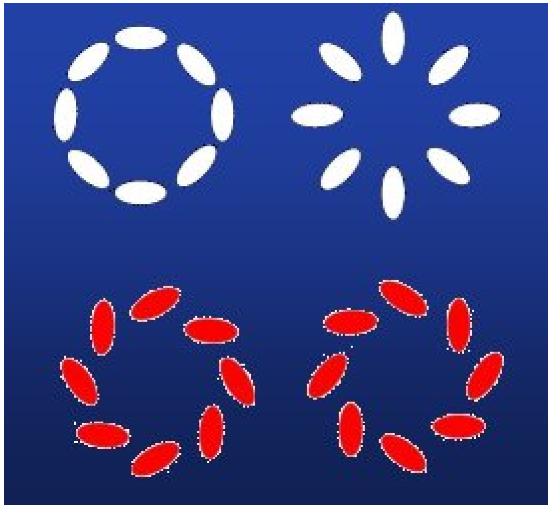
- Fortunately, the sky has given us some natural calibrators to control for PSF systematics: There is one star per square arcmin bright enough to measure the PSF in the image itself. Light from the stars passes through the same atmosphere and instrumentation, but is not subject to weak lensing distortions from the intergalactic medium. By interpolating the PSF's, we can deconvolve spurious shear from the true cosmic shear signal we are trying to measure. The key issue is how reliable is this deconvolution at very low shear levels.

Cosmic Shear Systematics: E-B mode Decomposition

The shear is a spin-2 field and consequently we can measure two independent ellipticity correlation functions. The lensing signal is caused by a gravitational potential and therefore should be curl-free. We can project the correlation functions into one that measures the divergence and one that measures the curl: E-B mode decomposition.

E-mode (curl-free)

B-mode (curl)



A residual B-mode is an indication of spurious shear in the analysis.

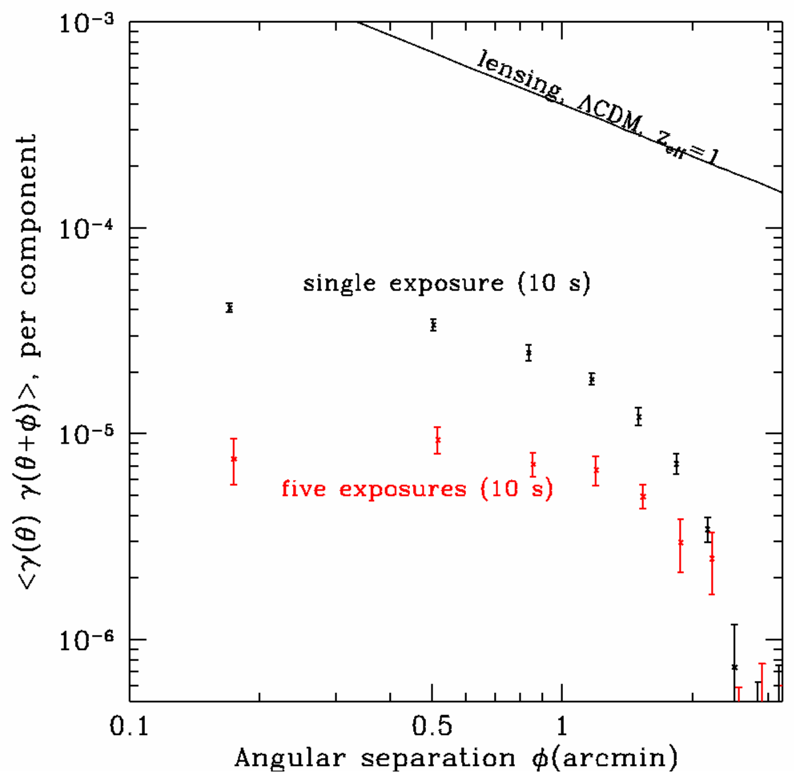
Residual Subaru Shear Correlation

Large Synoptic Survey Telescope

Test of shear systematics:
Use faint stars as proxies for galaxies, and calculate the shear-shear correlation.

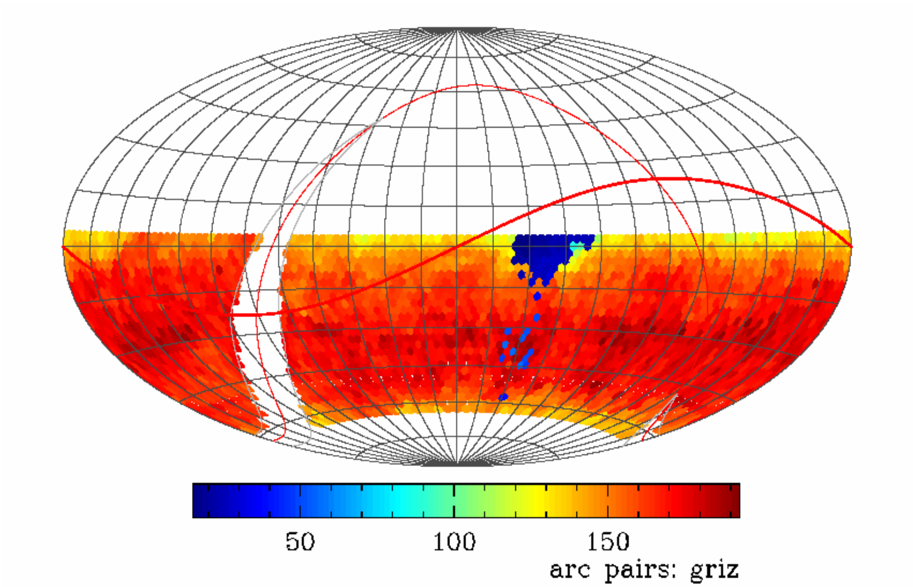
Compare with expected cosmic shear signal.

Conclusion: 500 exposures per sky patch will yield negligible PSF induced shear systematics.
Wittman (2005)



Measuring Shear Residuals Directly

- A key aspect of the LSST design is that we have very short exposure times (15 s). This enables us to obtain several hundred visits per field in each color over the life of the survey - nearly 1,000 visits overall.
- Using brighter galaxies, which are visible in every exposure, we can thus directly measure the residual spurious shear contributions as a function of environmental conditions.
- This allows us to optimize the shear extraction algorithms, leading to tremendous reduction in systematics.
- Experience in particle physics expts shows that the systematic errors fall faster than root N - more like 1/N.

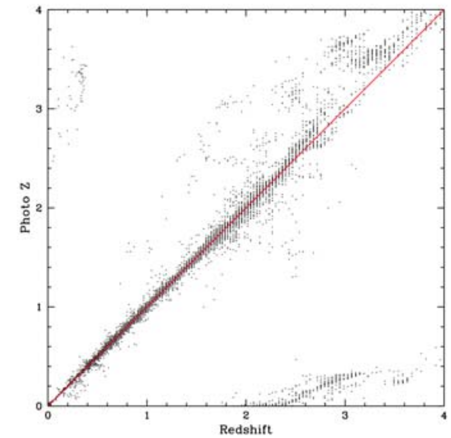


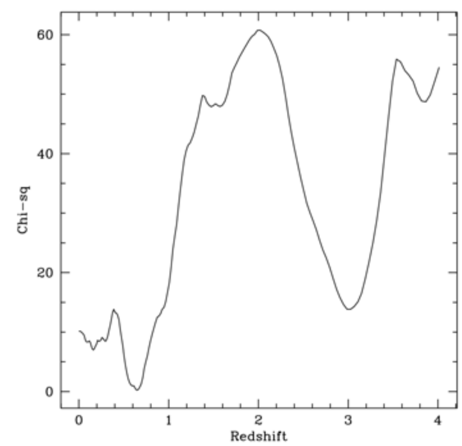
Systematics in Photo-z's

- Photometric redshift accuracy is limited by the statistical quality of the data and by the location of the key spectral features with respect to the passbands which are used.

- The dominant features are the Balmer and Lyman breaks at 400 nm and 91 nm, respectively. As these move through the bands, the noise in the photo-z inversion rises and falls.

- There can also be catastrophic failures due to multiple minima associated with confusion between these two features.



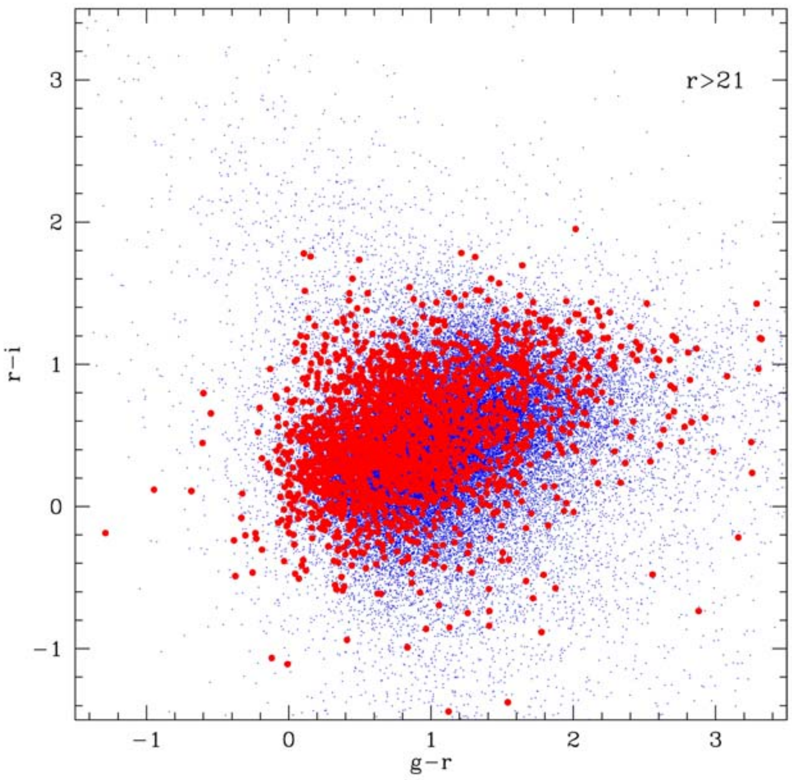


Systematics in Photo-z's

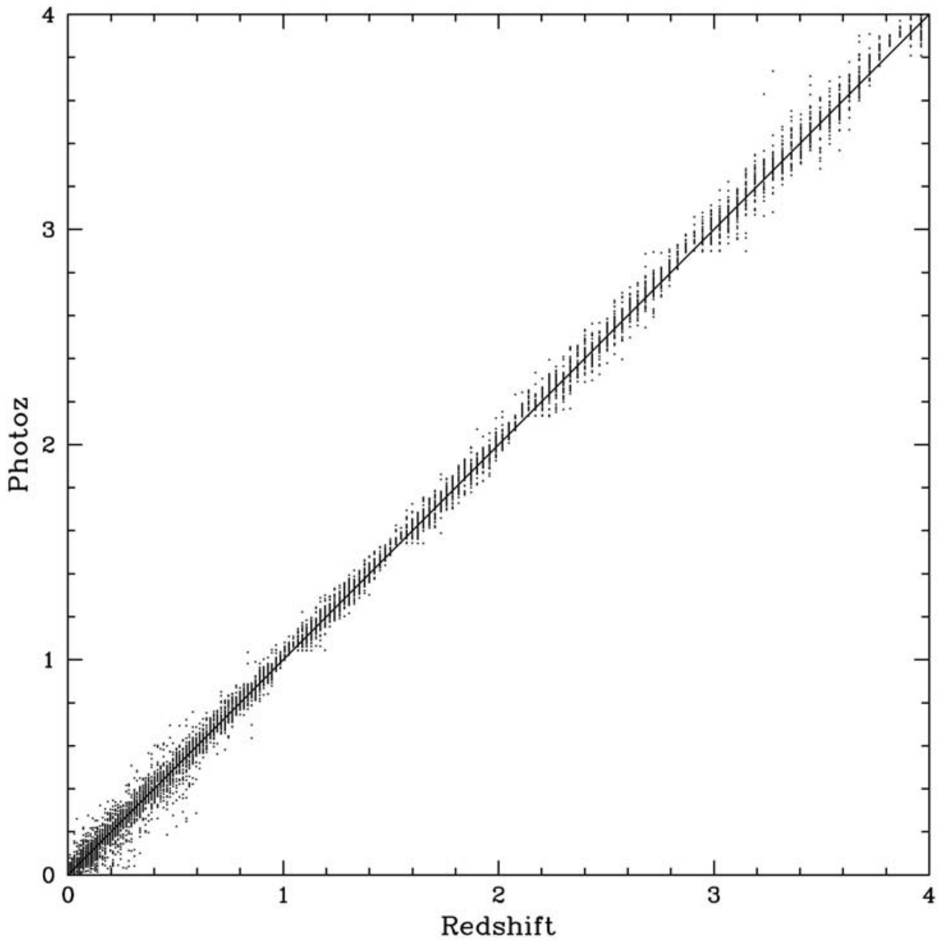
- There are various statistical issues that can be investigated using Monte Carlo techniques to quantify the impact of photo-z errors on dark energy parameter estimations. Priors on size and mag can help to reduce the catastrophic failutres.

- But we are still left with the fundamental issue of calibration, since we don't know the distribution of intrinsic galaxy spectra at higher redshifts.

- Brute force calibration would require an enormous number of spectroscopic measurements. Fortunately, it appears that making use of the intrinsic clustering properties of galaxies can reduce this number to a manageable level.



12-band Super Photo-z Training Set



Using angular correlations this training set enables LSST photo-z error calibration to better than required precision

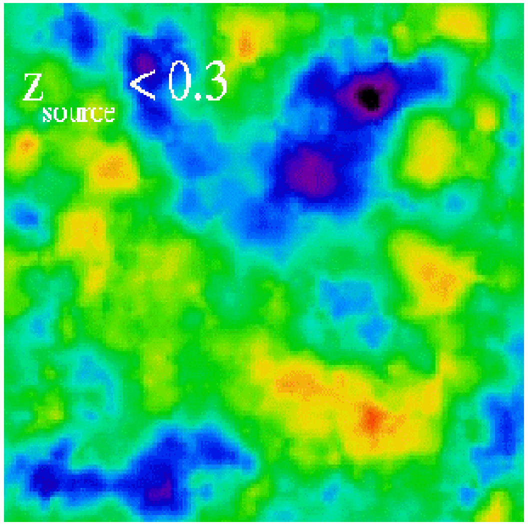
Systematic error:
0.003(1+z) *calibratable*
Need 20,000 spectroscopic redshifts overall.

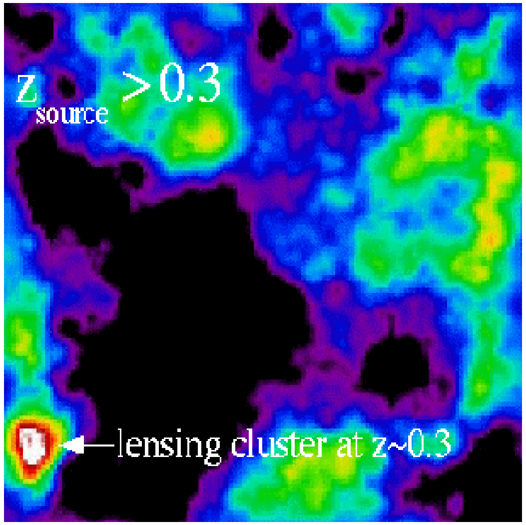
Clusters of Galaxies

- Clusters of galaxies are the most massive bound structures in the Universe, and both their number density and spatial power spectrum are sensitive to the growth of structure.

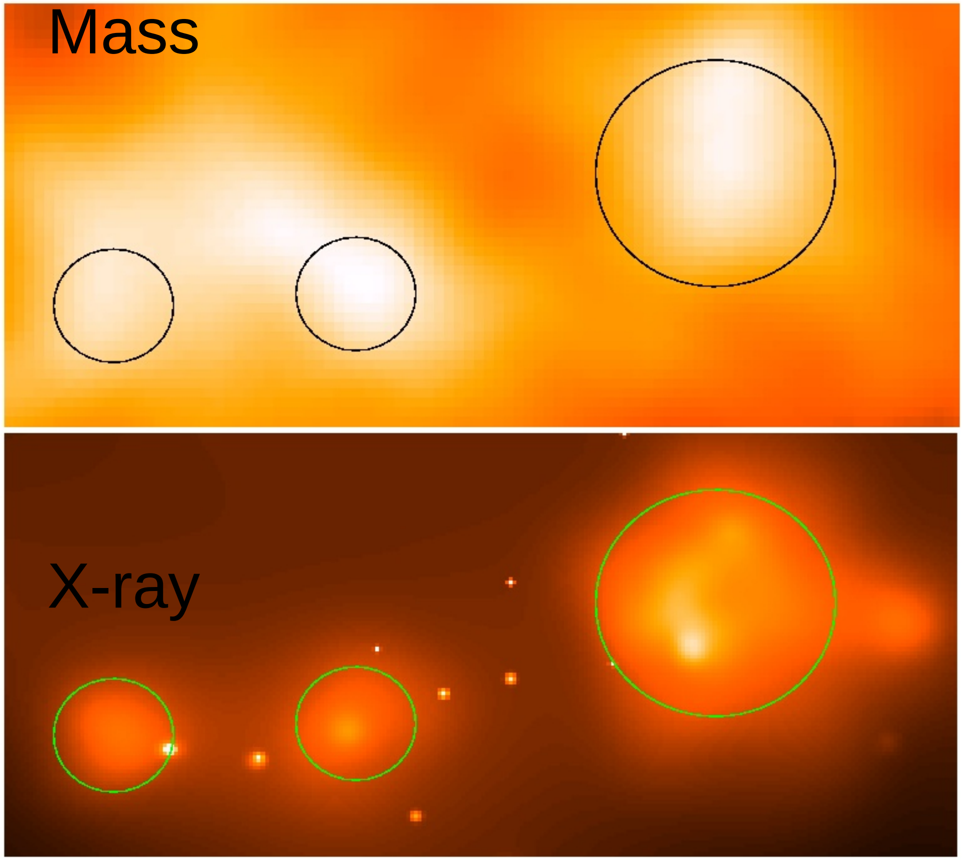
- LSST will detect clusters via weak gravitational lensing and measure their redshifts from the galaxy colors. ~ 200,000 clusters will be discovered.

- Weak lensing probes the dark matter directly. Baryonic tracers can be biased and must be calibrated.





Some Clusters Detected via WL have been Confirmed in X-Ray Light



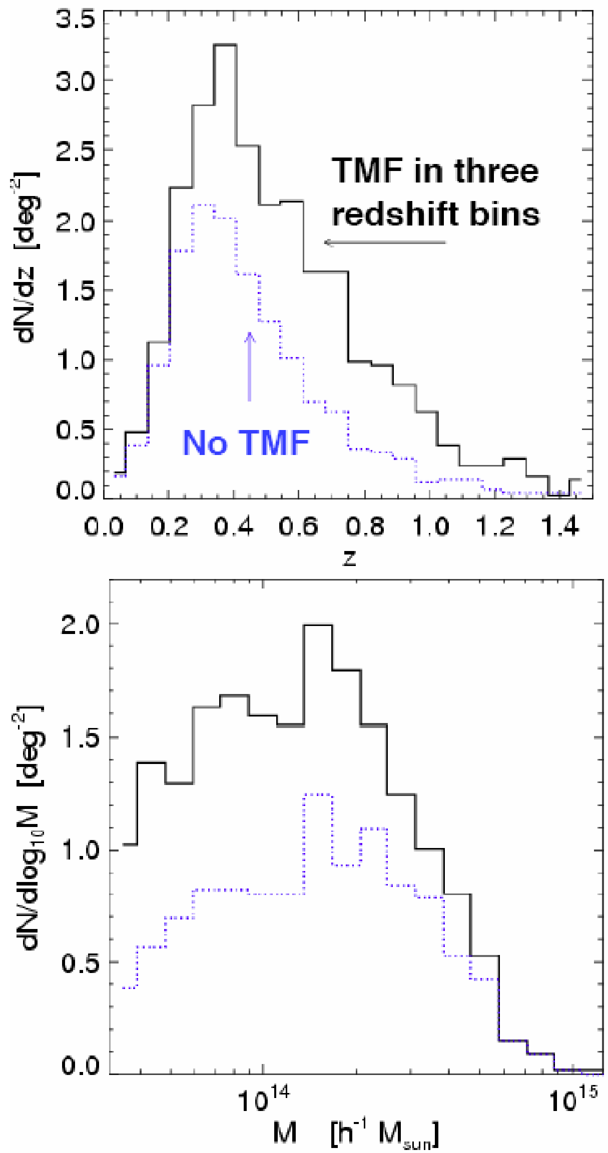
Courtesy Tony Tyson and the DLS Project Team

Cluster Counting with WL Tomograhpy

- *dN/dMdz* constrains DE models via the dependences on the co-moving volume element, *dV/dΩdz,* and on the exponential growth of structure, $\delta(z)$.

- Since WL measures DM mass directly, it does not suffer by the various forms of baryon bias and uncertainties in gas dynamical processes.

- With a sky coverage of 18,000 square degrees, LSST will find 200,000 clusters. A sample this size will yield a measurement of *w* to 2-3%.



From Haiman et al. (2005)

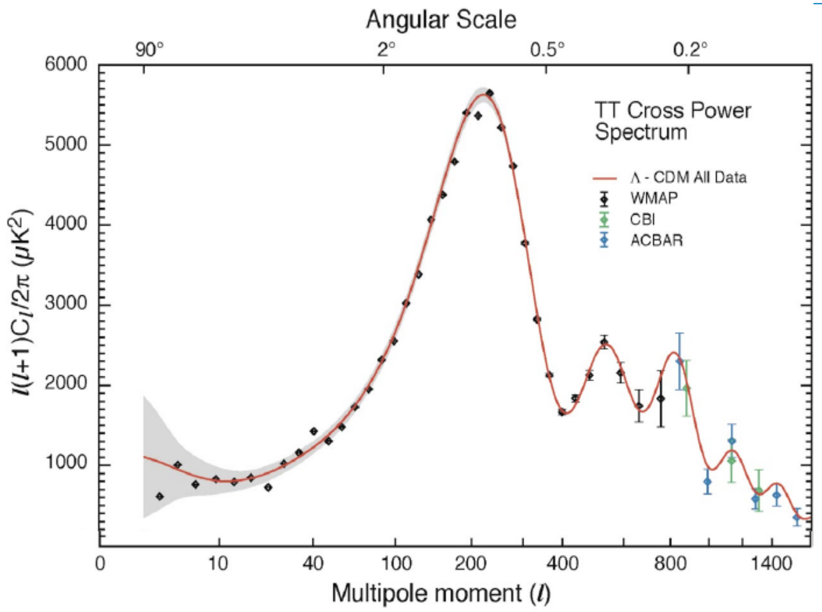
Baryon Acoustic Oscillations

- Prior to recombination, the baryons are tightly coupled to the radiation in the universe.

- An overdensity perturbation gives rise to an acoustic wave in this tightly coupled fluid, which propagates outward at the sound speed, $c/\sqrt{3}$.

- After recombination, the matter and radiation decouple. The sound speed drops to zero, and the propagating acoustic wave stops.

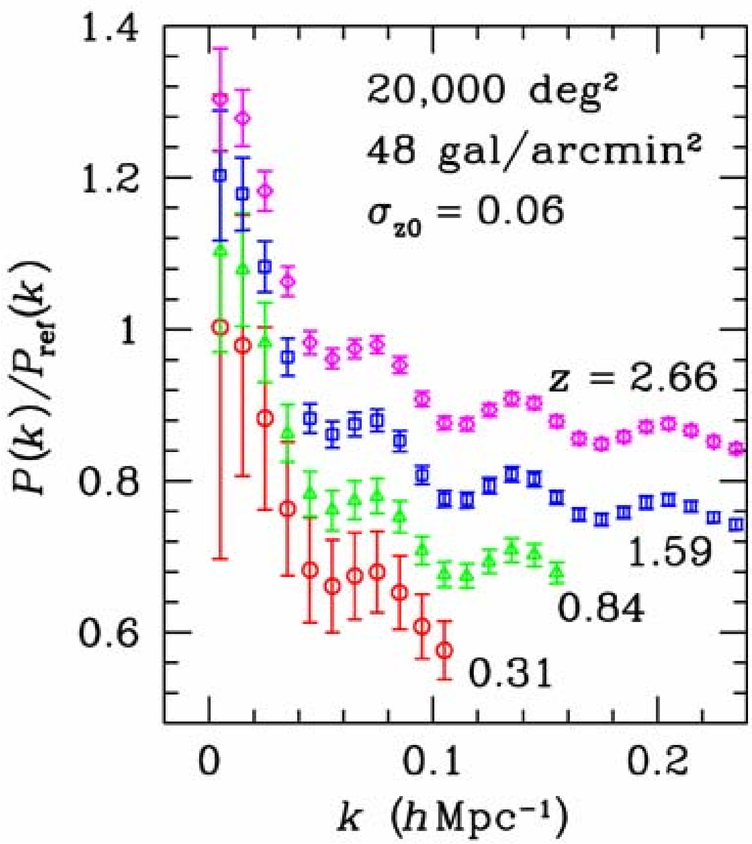
- This gives rise to a characteristic scale in the universe: 150 Mpc, the distance the sound waves have traveled at the time of recombination.



These acoustic waves are visible as the peaks in the CMB power spectrum.

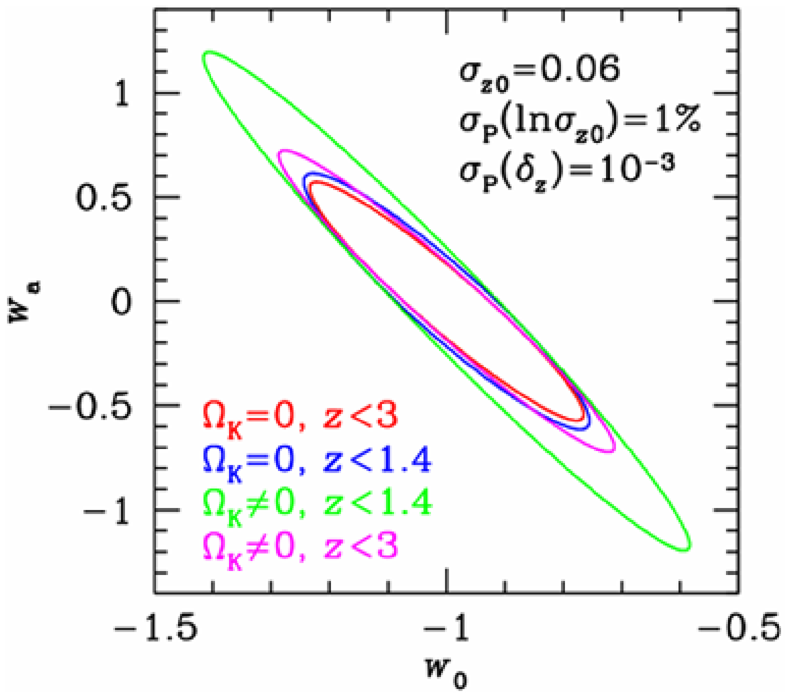
Baryon Acoustic Oscillations

- Following recombination, gravitational instability causes the birth of stars and galaxies.
- The gravitational coupling between the dark matter and the baryons creates an imprint of these acoustic oscillations in the galaxy distribution.
- This persists as the universe expands, although it gets weaker with time.
- The effect can be measured in the power spectrum of the galaxy distribution.



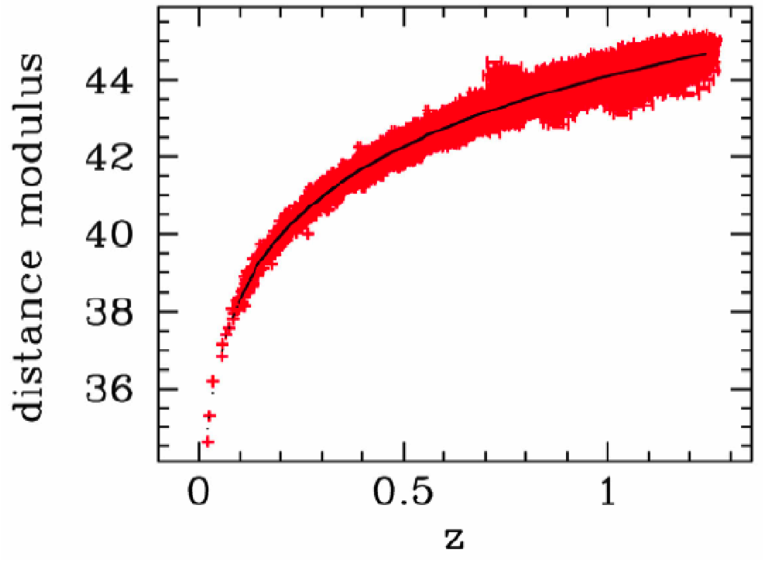
Baryon Acoustic Oscillations

- Since the physical scale is known precisely, the angular scale of the measured peaks provides an angular diameter redshift relation.
- The "new" feature introduced by measurement of the BAO's is the ability to constrain the expansion history at higher redshift, before DE became dominant.
- This is important for breaking the degeneracy between non-zero curvature and alternate forms of dark energy. Allowing Ω_K to depart from zero, weakens constraints on w and w_a.

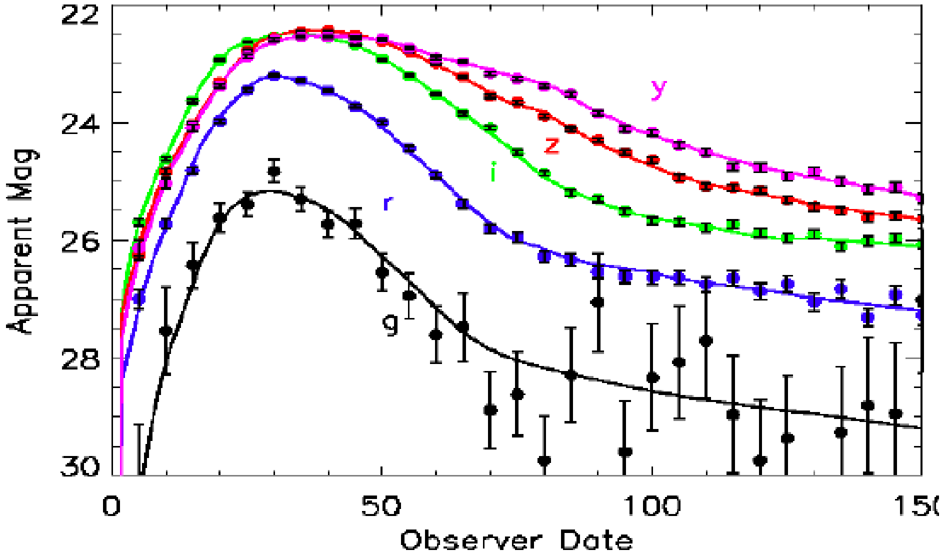


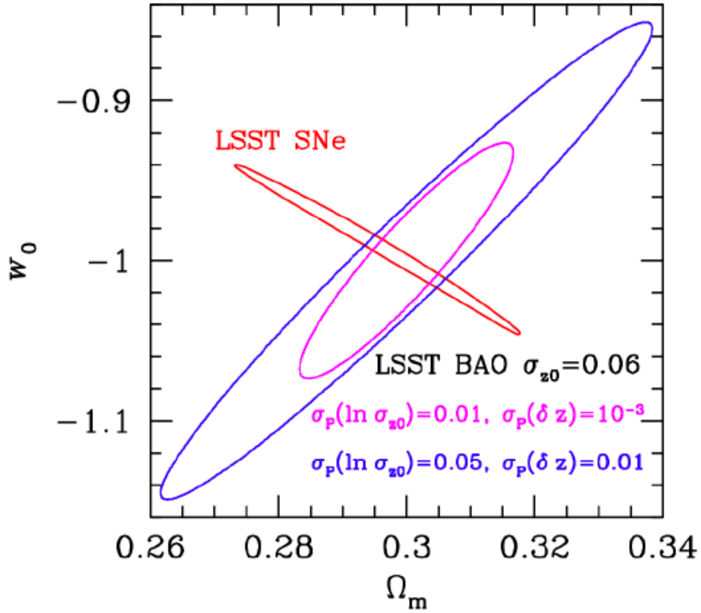
Type 1a Supernovae

- LSST will discover a very, very large number of Type 1a SNe, in both its normal survey mode (~ 280,000 yr^{-1}), and in a "deep" survey mode (~ 30,000 yr^{-1}).
- These can be used to study possible systematics, as well as to constrain cosmological parameters.
- The SNe discovered in the deep mode, will have well-sampled, multi-color light curves - sufficient for deriving redshifts directly from the photometric data.



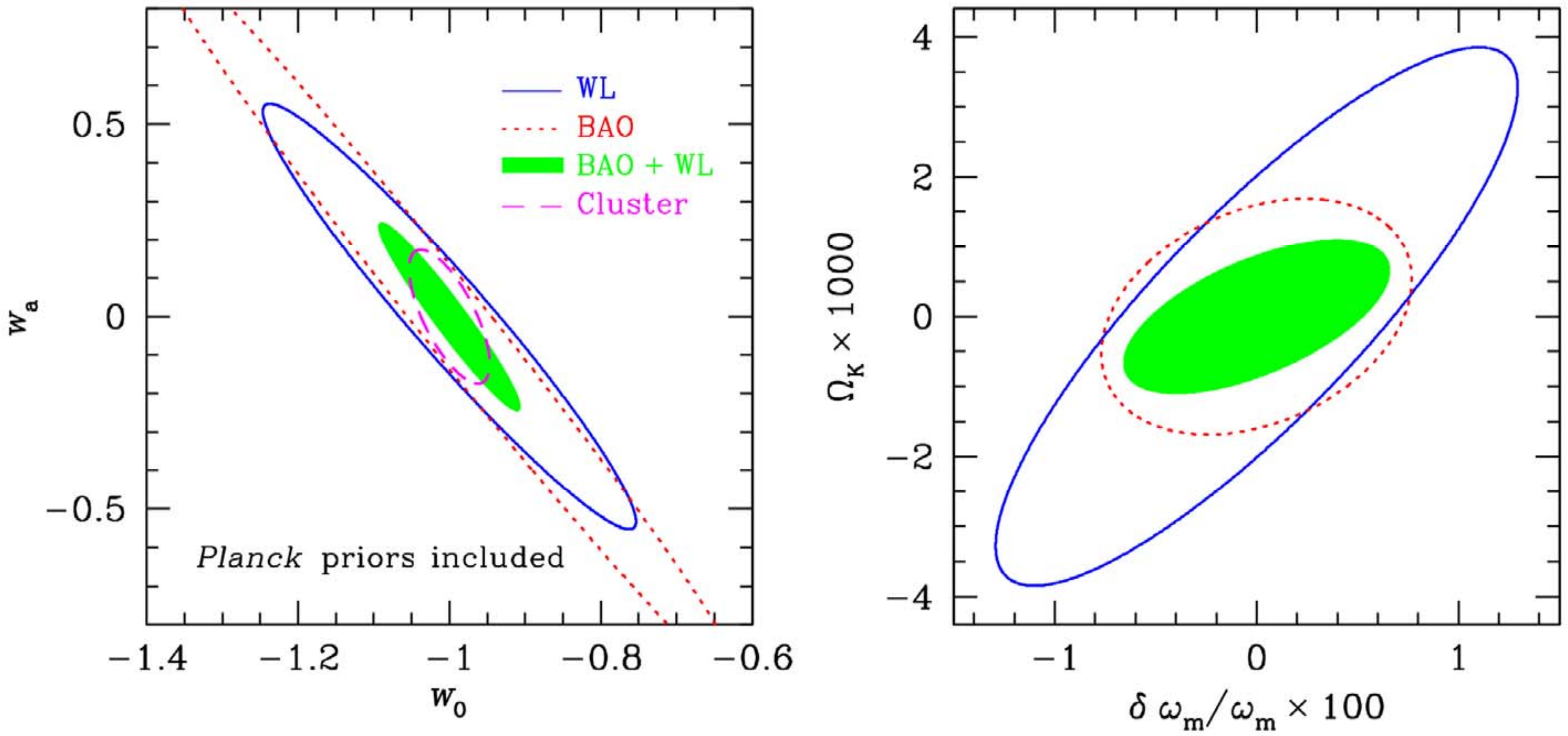
Type 1a Supernovae





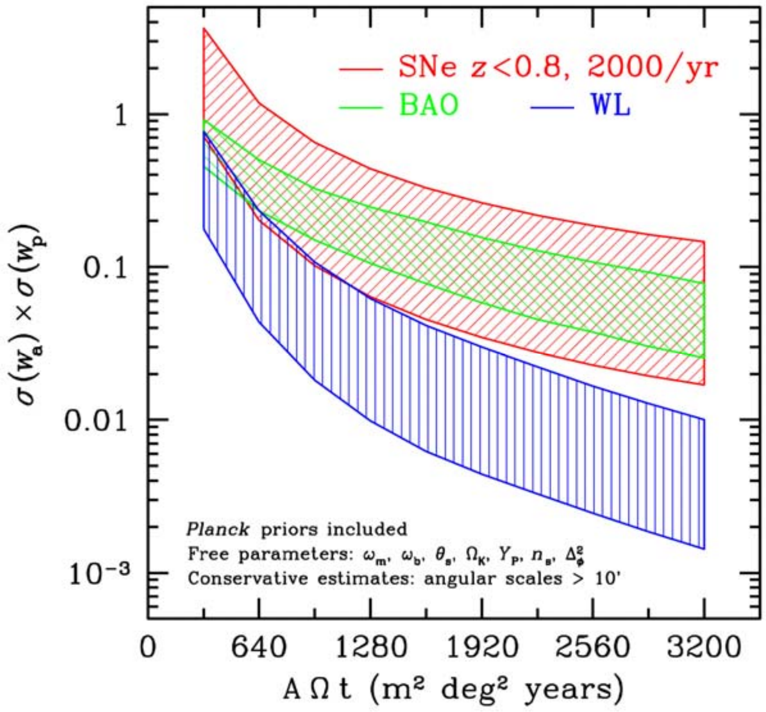
LSST Precision on Dark Energy

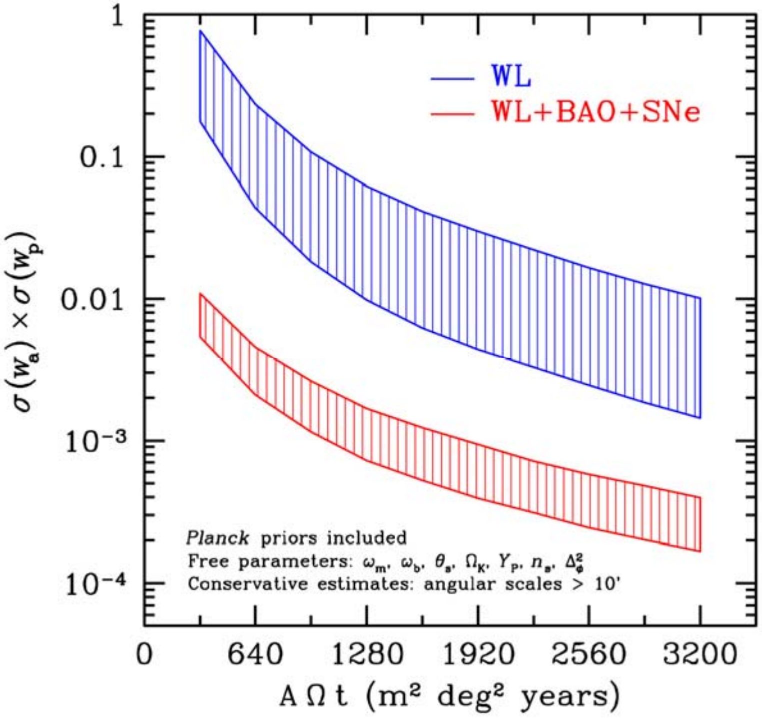
Large Synoptic Survey Telescope



Zhan (2006)

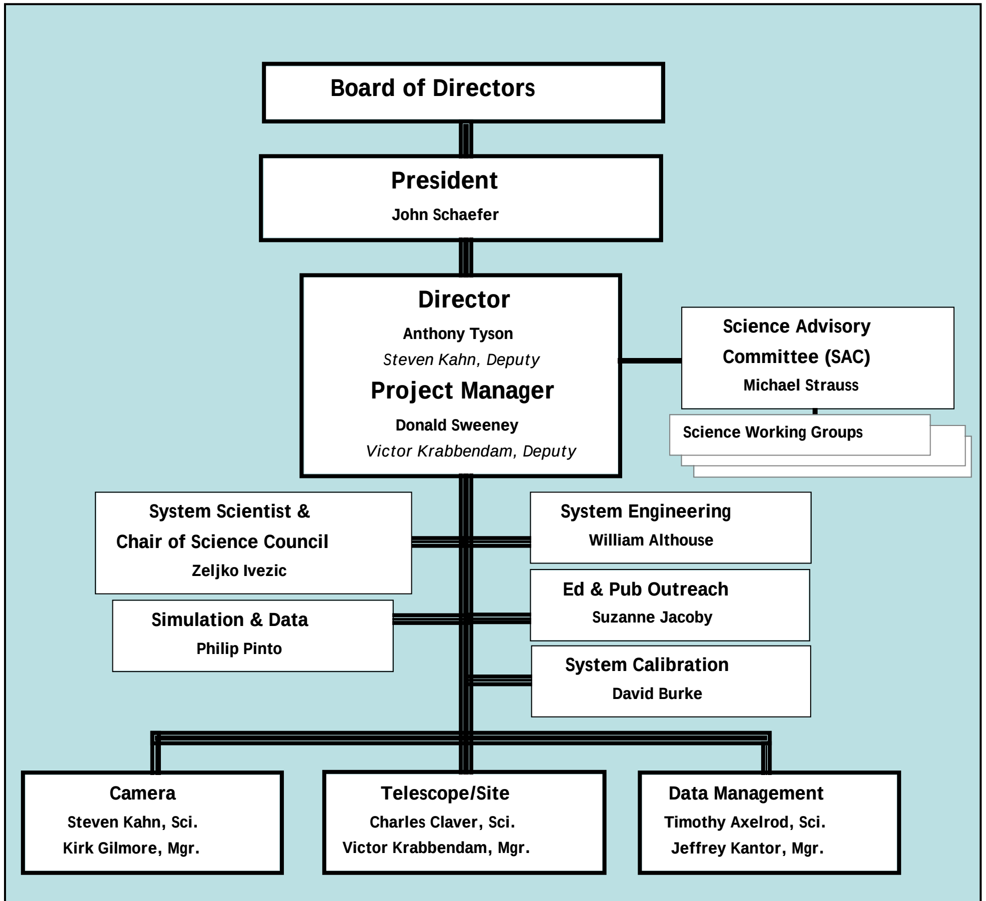
Precision vs Integrated Luminosity





LSST Project Organization

- The LSST is a public/private project with public support through NSF-AST and DOE-OHEP.
- Private support is devoted primarily to project infrastructure and fabrication of the primary/tertiary and secondary mirrors, which are long-lead items.
- NSF support is proposed to fund the telescope. DOE support is proposed to fund the camera.
- Both agencies would contribute to data management and operations.



LSST Organization Chart

The LSST Corporation

- The project is overseen by the LSSTC, a 501(c)3 non-profit Arizona corporation based in Tucson.
- LSSTC is the recipient of private funding, and is the Principal Investigator organization for the NSF D&D funding.

There are 23 LSSTC Institutional Members

- Brookhaven National Laboratory
- California Institute of Technology
- Carnegie-Mellon University
- Columbia University
- Google Corporation
- Harvard-Smithsonian Center for Astrophysics
- Johns Hopkins University
- Las Cumbres Observatory
- Lawrence Livermore National Laboratory
- National Optical Astronomy Observatory
- Princeton University
- Purdue University
- Research Corporation
- Stanford Linear Accelerator Center
- Stanford University –KIPAC
- The Pennsylvania State University
- University of Arizona
- University of California, Davis
- University of California, Irvine
- University of Illinois at Champaign-Urbana
- University of Pennsylvania
- University of Pittsburgh
- University of Washington

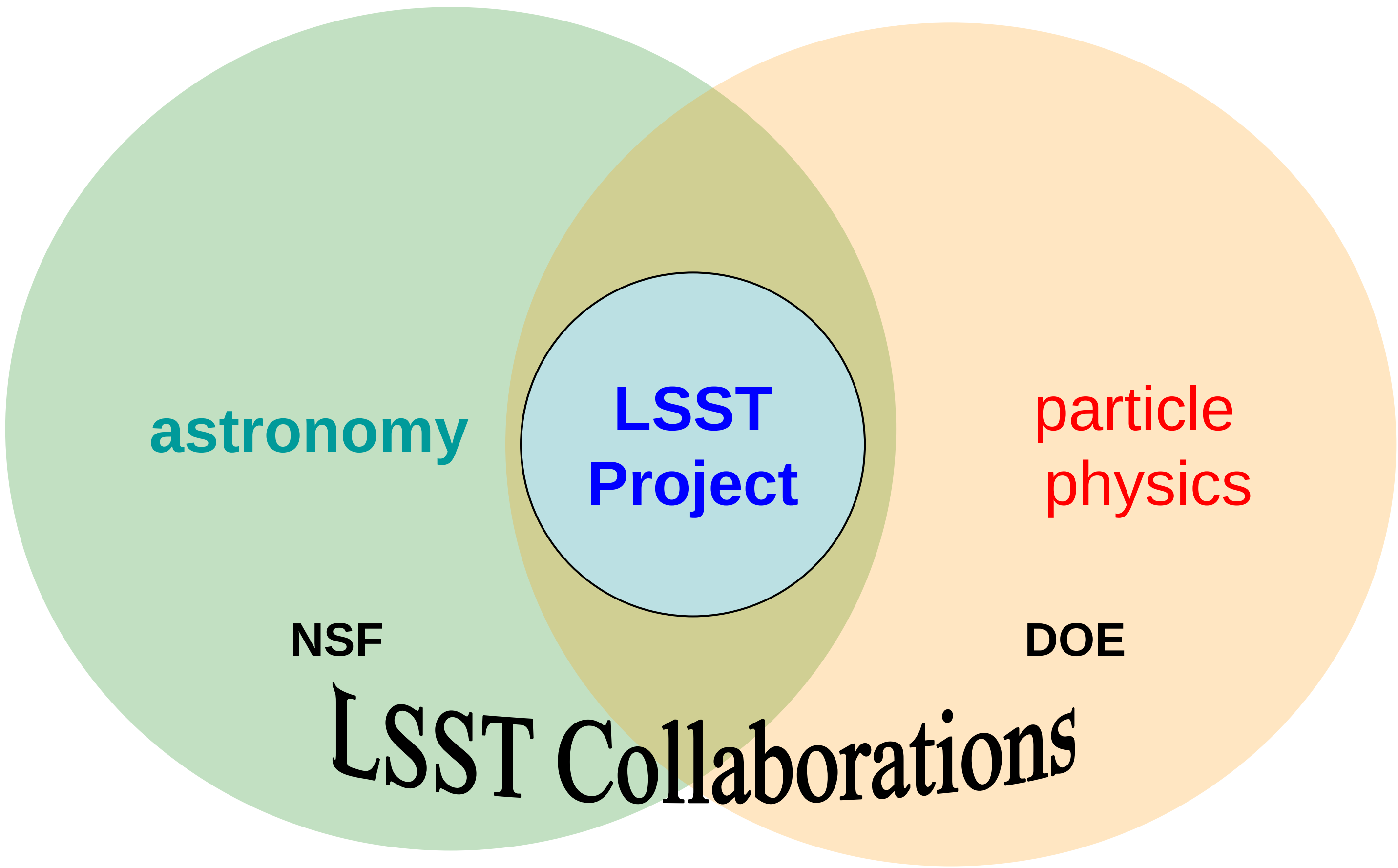
International Participation

- Informal discussions have been held with both small and large institutions in Europe and Asia.

- The most concrete negotiations have been with IN2P3 in France. A consortium of 6 laboratories (APC, CC-IN2P3, LAL, LMA, LPSC, LPNHE) is participating in the R&D for the camera and the system calibration, with the intention contributing to the construction as well.

- Discussions with ESO are on-going. The need for a large imaging ground-based survey facility has been recognized explicitly by ESO, but it is still unclear how this will fit into the long-range plan for the observatory.

LSST integrates Astronomy & Physics communities



LSST Science Collaborations

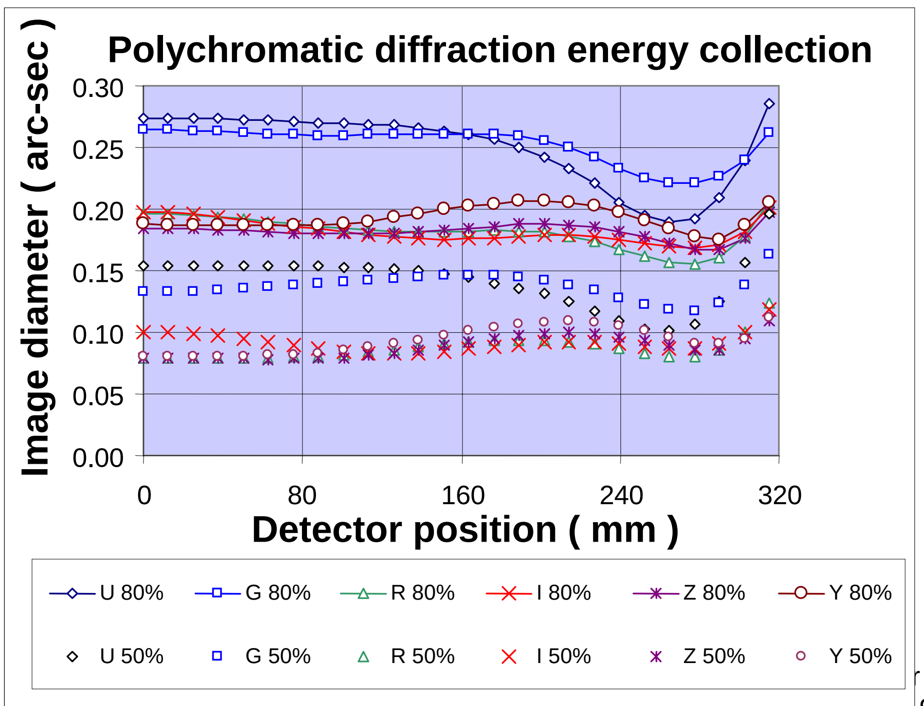
1. Supernovae: M. Wood-Vasey (CfA)
2. Weak lensing: D. Wittman (UCD) and B. Jain (Penn)
3. Stellar Populations: Abi Saha (NOAO)
4. Active Galactic Nuclei: Niel Brandt (Penn State)
5. Solar System: Steve Chesley (JPL)
6. Galaxies: Harry Ferguson (STScI)
7. Transients/variable stars: Shri Kulkarni (Caltech)
8. Large-scale Structure/BAO: Andrew Hamilton (Colorado)
9. Milky Way Structure: Connie Rockosi (UCSC)
10. Strong gravitational lensing: Phil Marshall (UCSB)

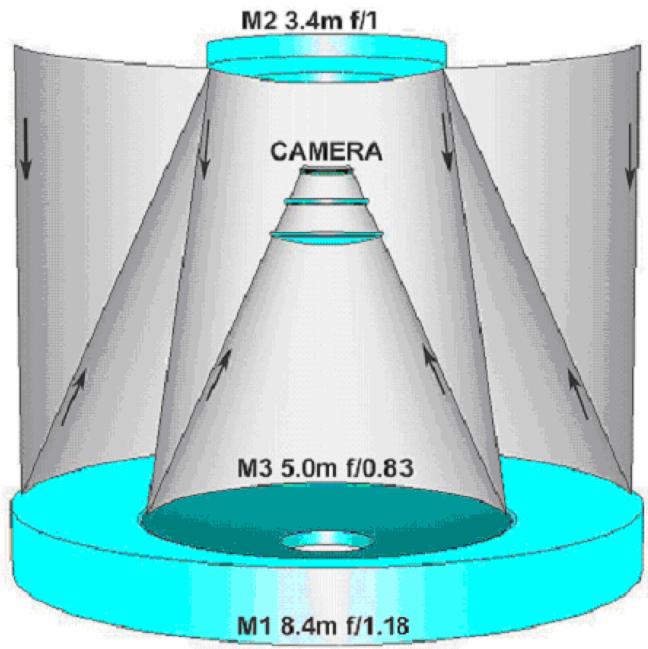
171 signed on already, from member institutions and project team.

LSST Optical Design

Large Synoptic Survey Telescope

- *f/1.23*
- **< 0.20 arcsec FWHM images in six bands: 0.3 - 1 μm**
- **3.5 ° FOV → Etendue = 319 $m^2 deg^2$**



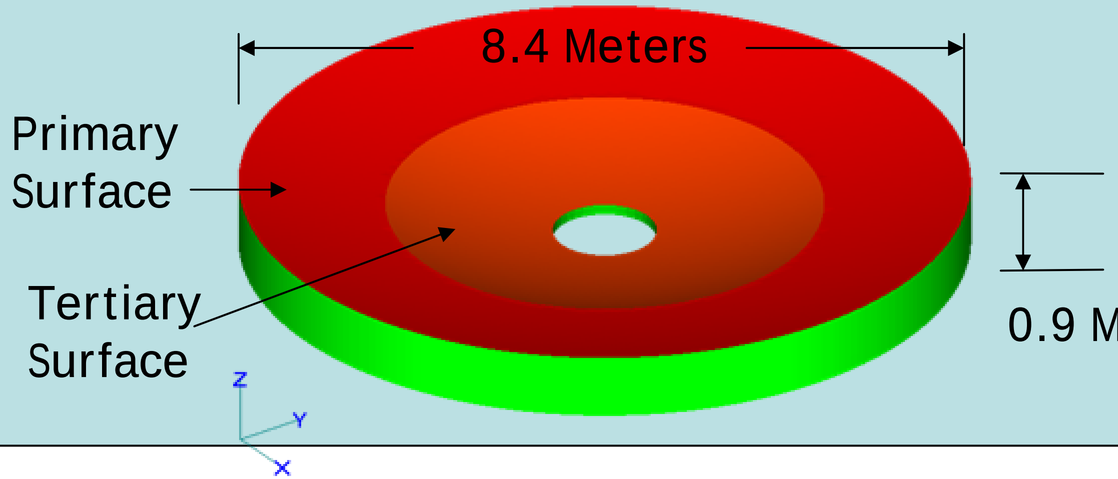


LSST optical layout

Mirror Designs

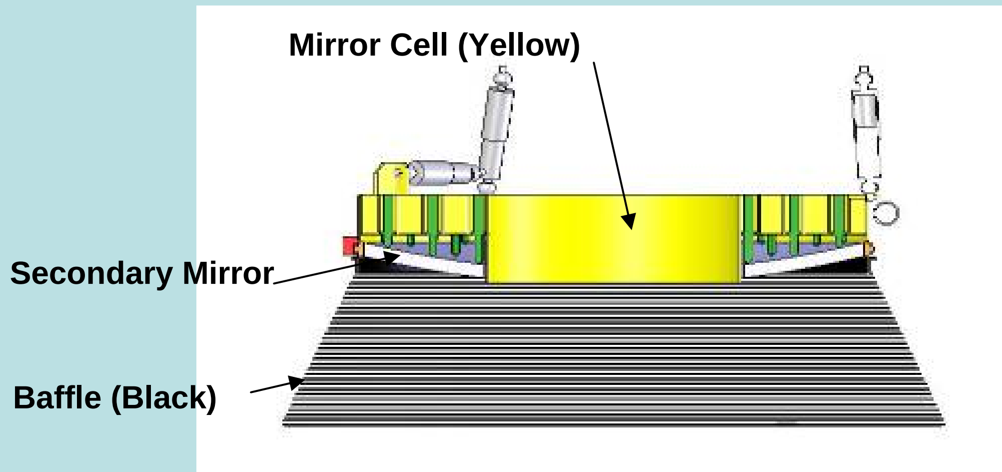
Primary/Tertiary Mirror

- *Unique Monolithic Mirror: Primary and Tertiary Surfaces Polished Into Single Substrate*
- *Cast Borosilicate Design*



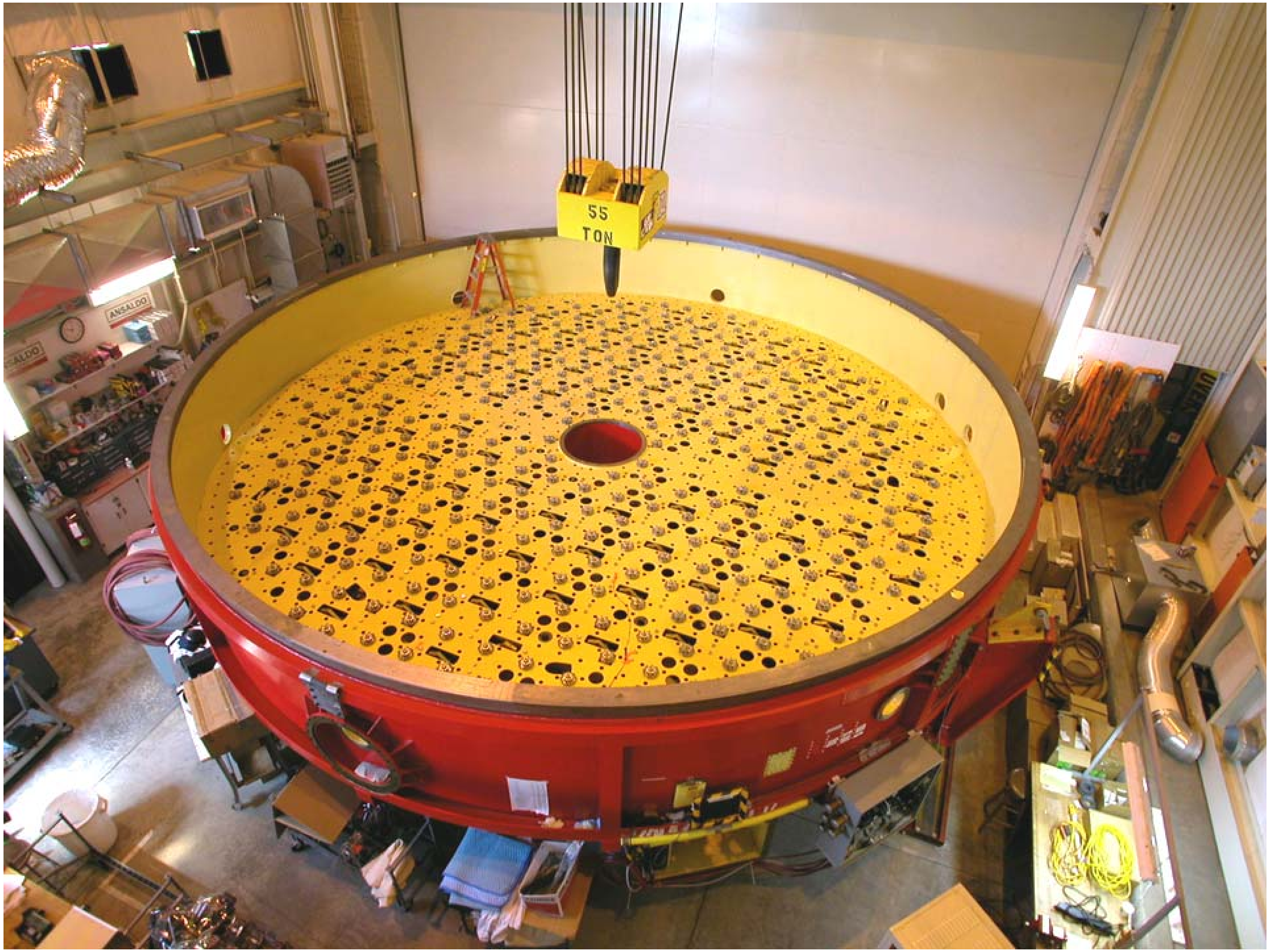
Secondary Mirror

- *Thin Meniscus Low Expansion Glass Design for Secondary Mirror*
- *102 Support Actuators*

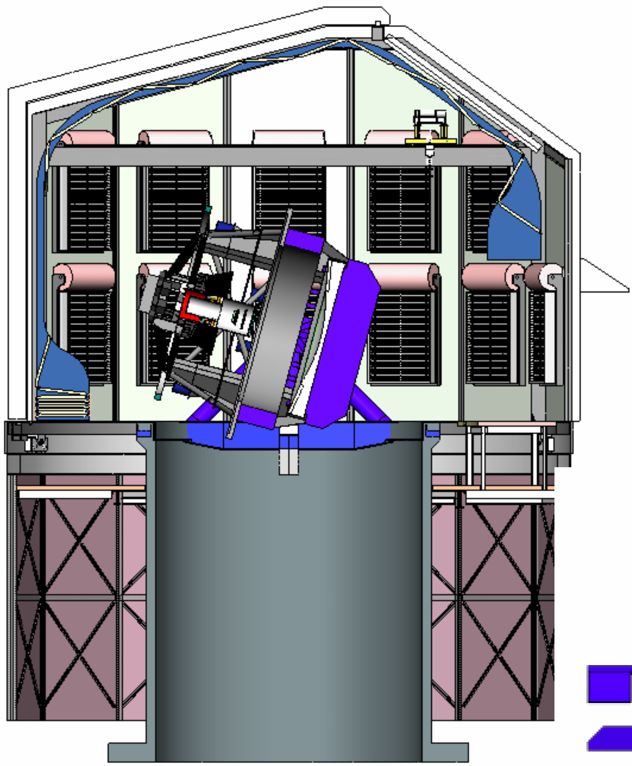


Spin Casting of large optics at the U of A

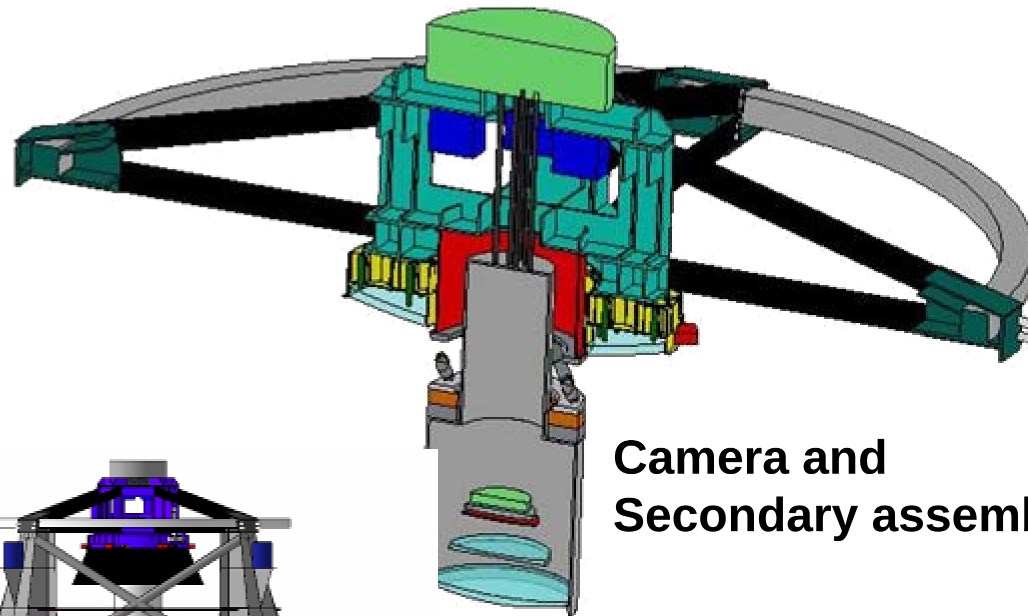
The LBT 8.4m mirror cell with active optics



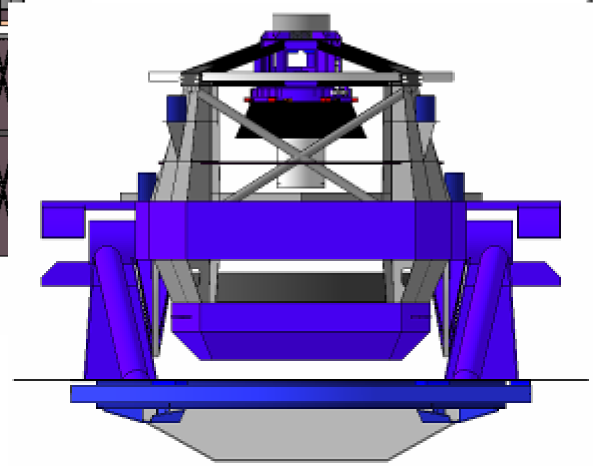
The Telescope Mount and Dome



Carrousel dome

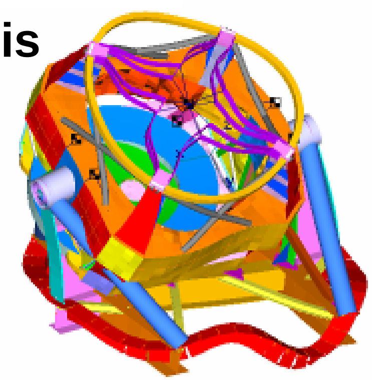


Camera and Secondary assembly

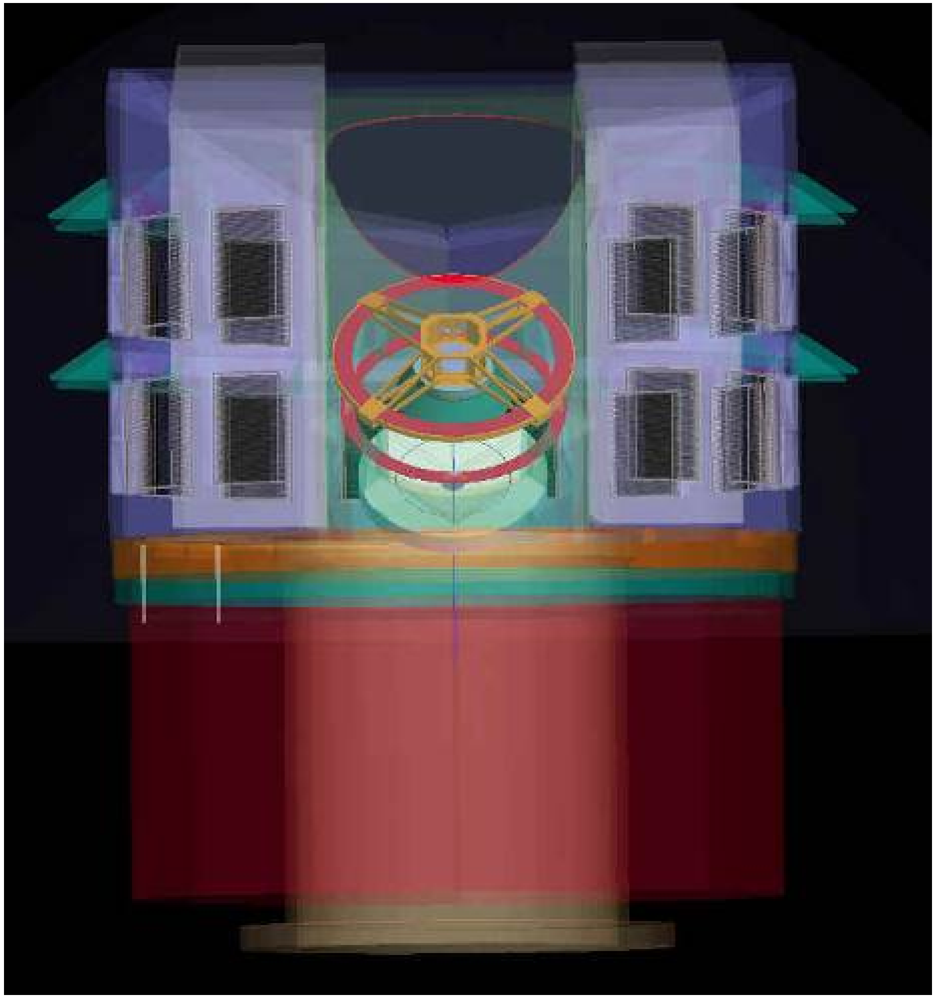


Altitude over azimuth configuration

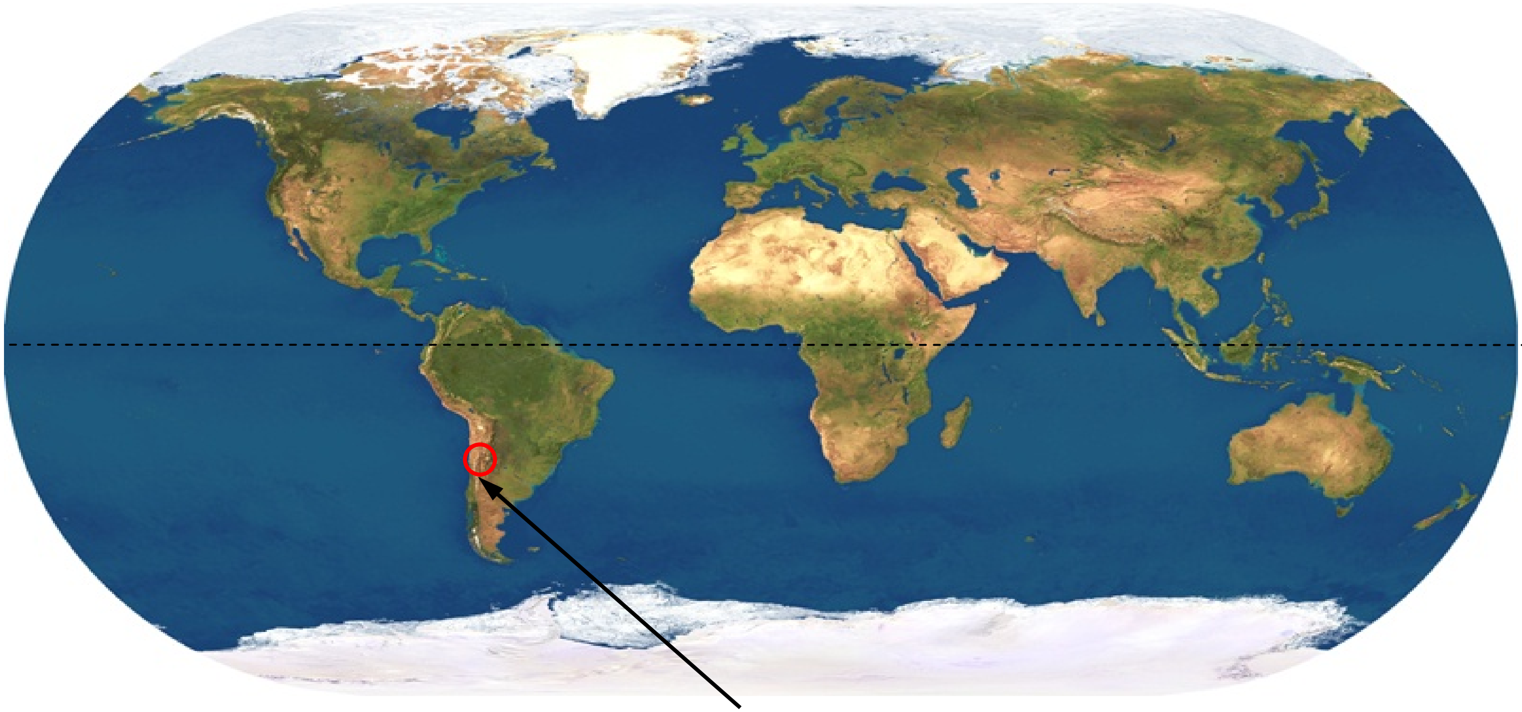
Finite element analysis



Rendering of the Telescope in its Dome



LSST will be Sited on Cerro Pachon in Chile

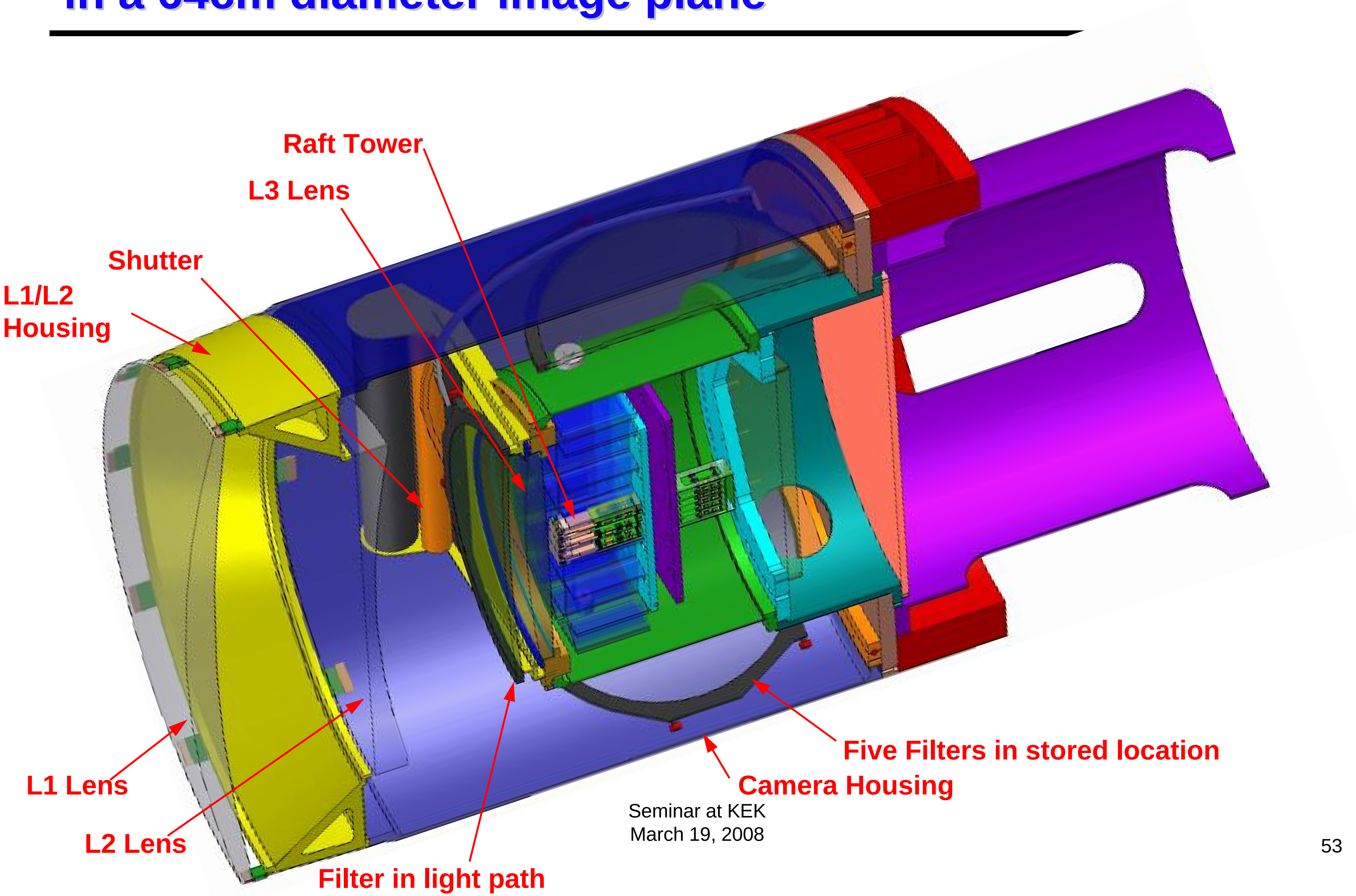


Cerro Pachón

The LSST will be on El Penon peak in Northern Chile in an NSF compound

1.5m photometric calibration telescope

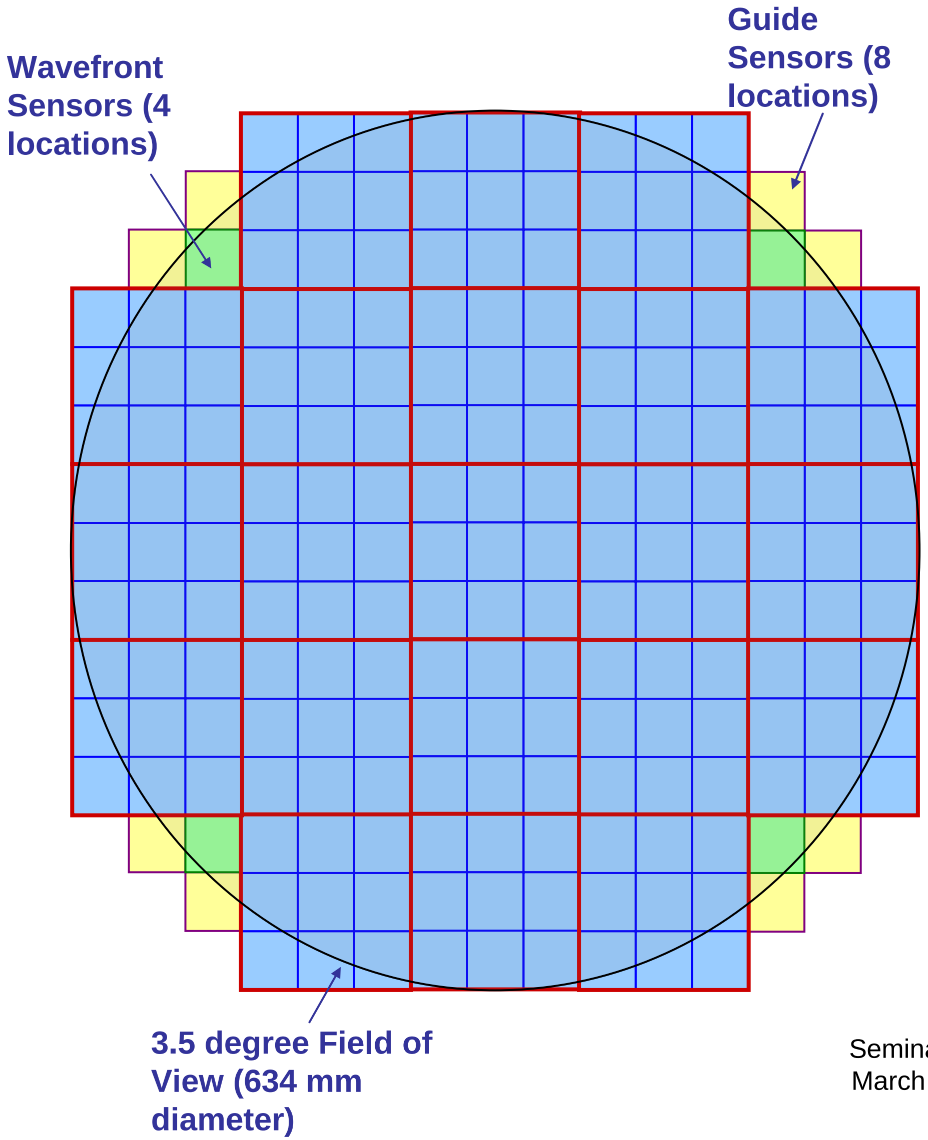
The LSST camera will have 3 Gigapixels in a 64cm diameter image plane



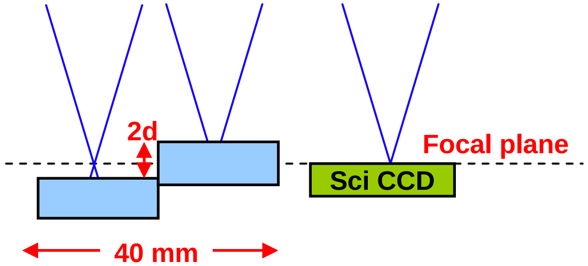
Camera Challenges

- Detector requirements:
  - 10 μm pixel size
  - Pixel full-well > 90,000 e^-
  - Low noise (< 5 e^- rms), fast (< 2 sec) readout (→ < –30 C)
  - High QE 400 – 1000 nm
  - All of above exist, but not simultaneously in one detector
- Focal plane position precision of order 3 μm
- Package large number of detectors, with integrated readout electronics, with high fill factor and serviceable design
- Large diameter filter coatings
- Constrained volume (camera in beam)
  - Makes shutter, filter exchange mechanisms challenging
- Constrained power dissipation to ambient
  - To limit thermal gradients in optical beam
  - Requires conductive cooling with low vibration

The LSST Focal Plane



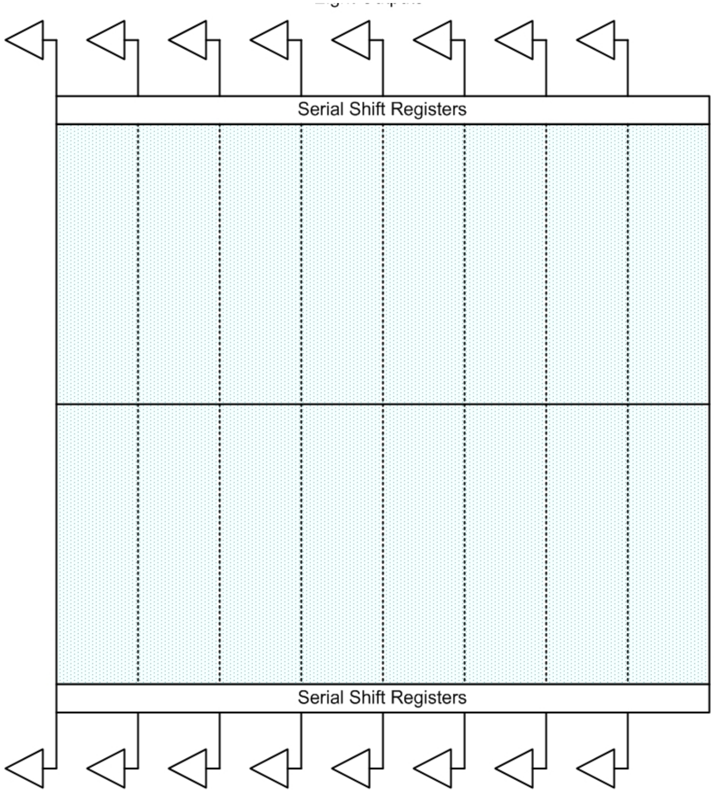
Wavefront Sensor Layout

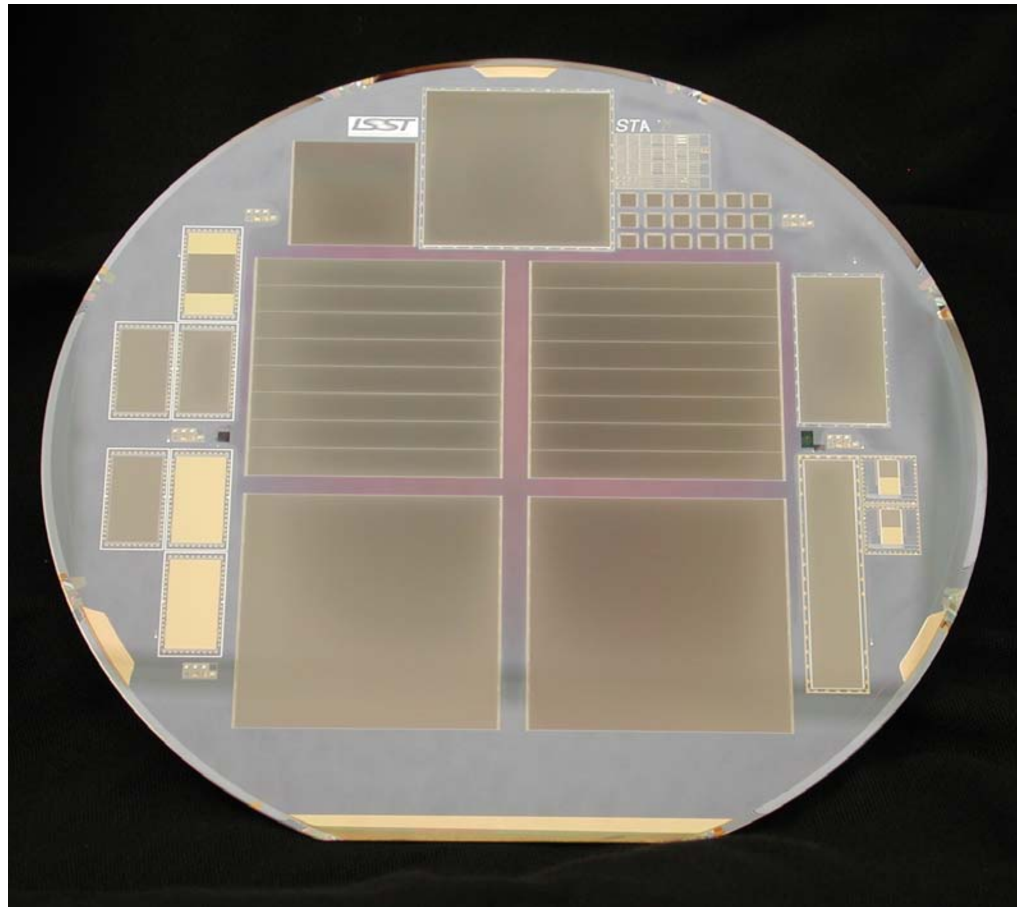


Curvature Sensor Side View Configuration

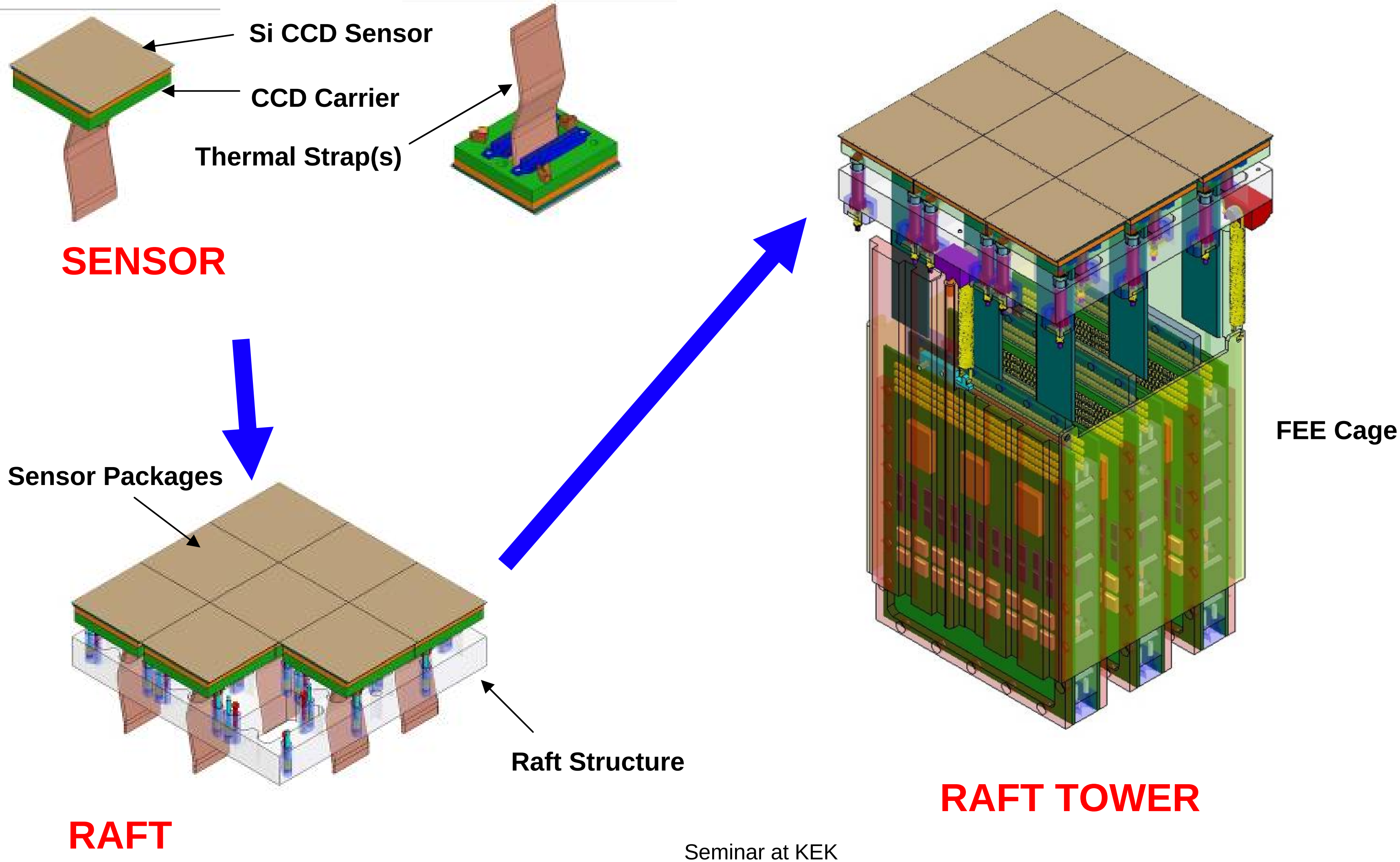
The LSST CCD Sensor

16 segments/CCD
200 CCDs total
3200 Total Outputs

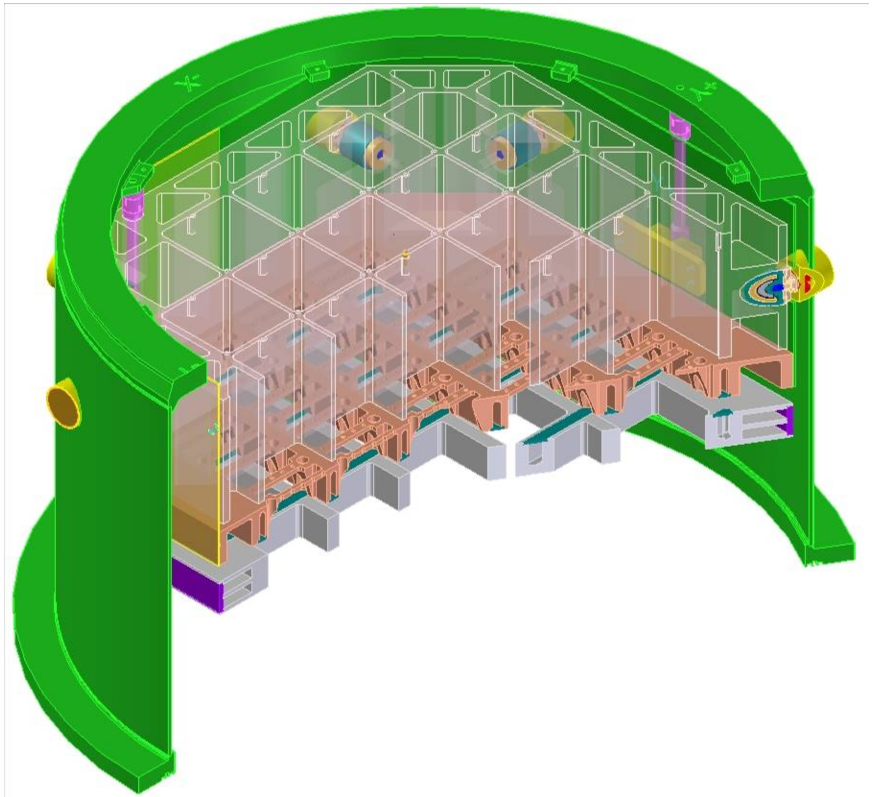


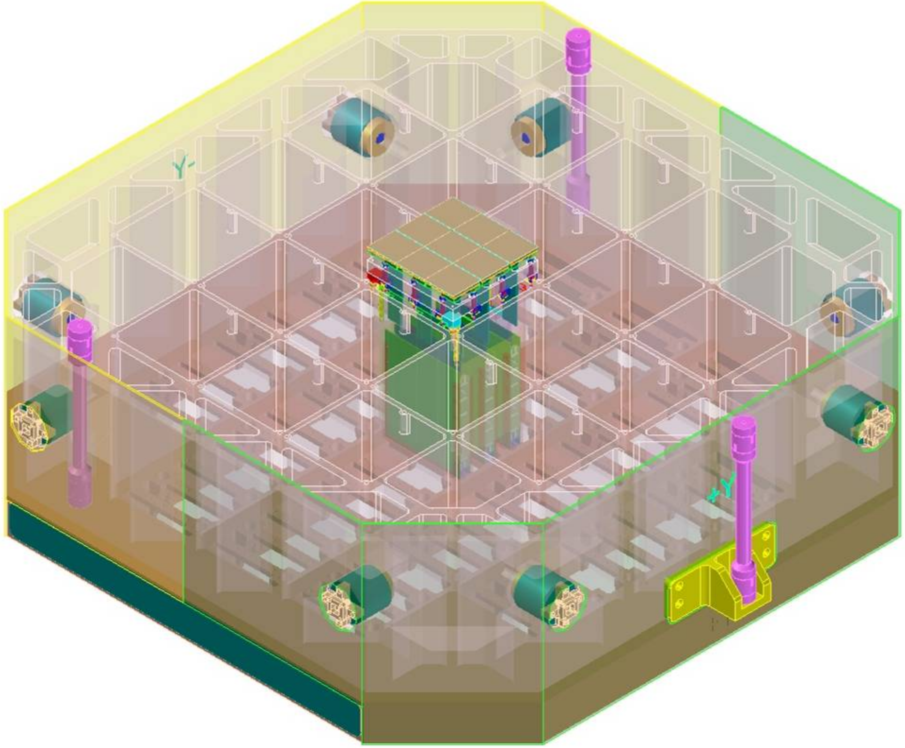


Raft Towers

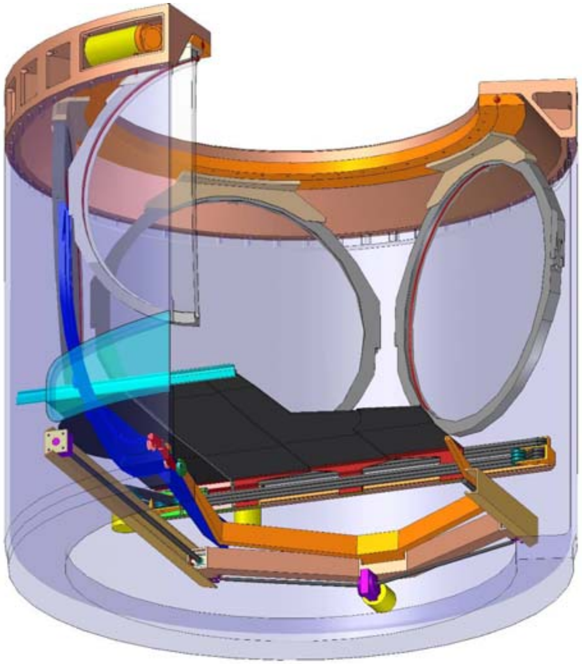

Si CCD Sensor
CCD Carrier
Thermal Strap(s)
SENSOR
Sensor Packages
Raft Structure
RAFT
FEE Cage
RAFT TOWER

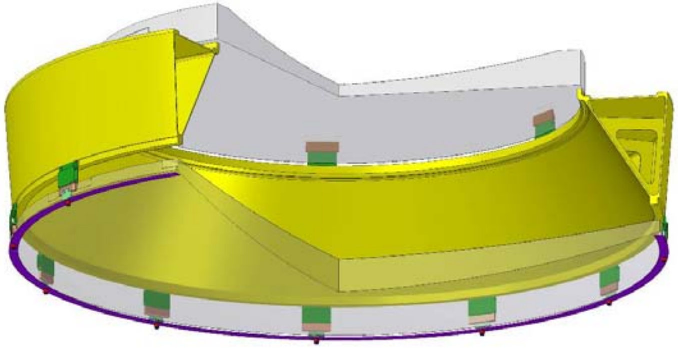
Cryosat Assembly

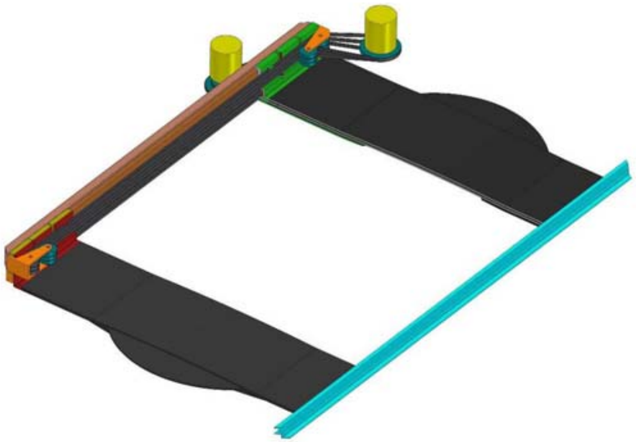


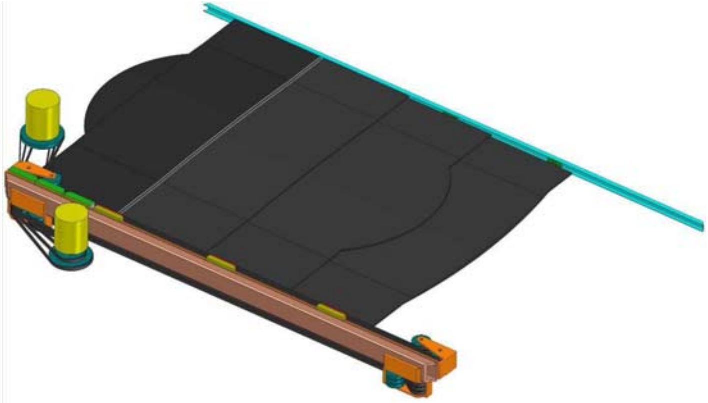


Camera Body and Mechanisms





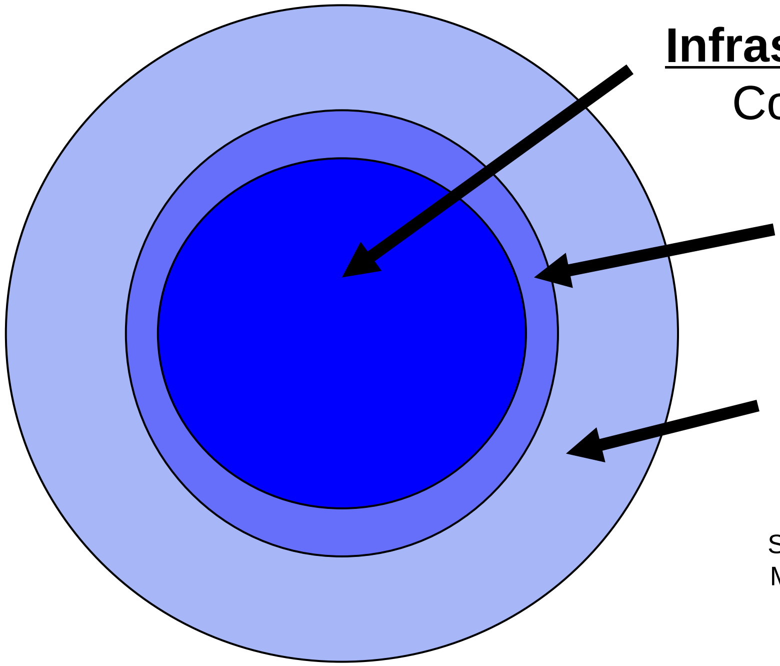




The LSST Data Management Challenge:

LSST generates 6GB of raw data every 15 seconds that must be calibrated, processed, cataloged, indexed, and queried, etc. often in real time

LSST Data Management Model



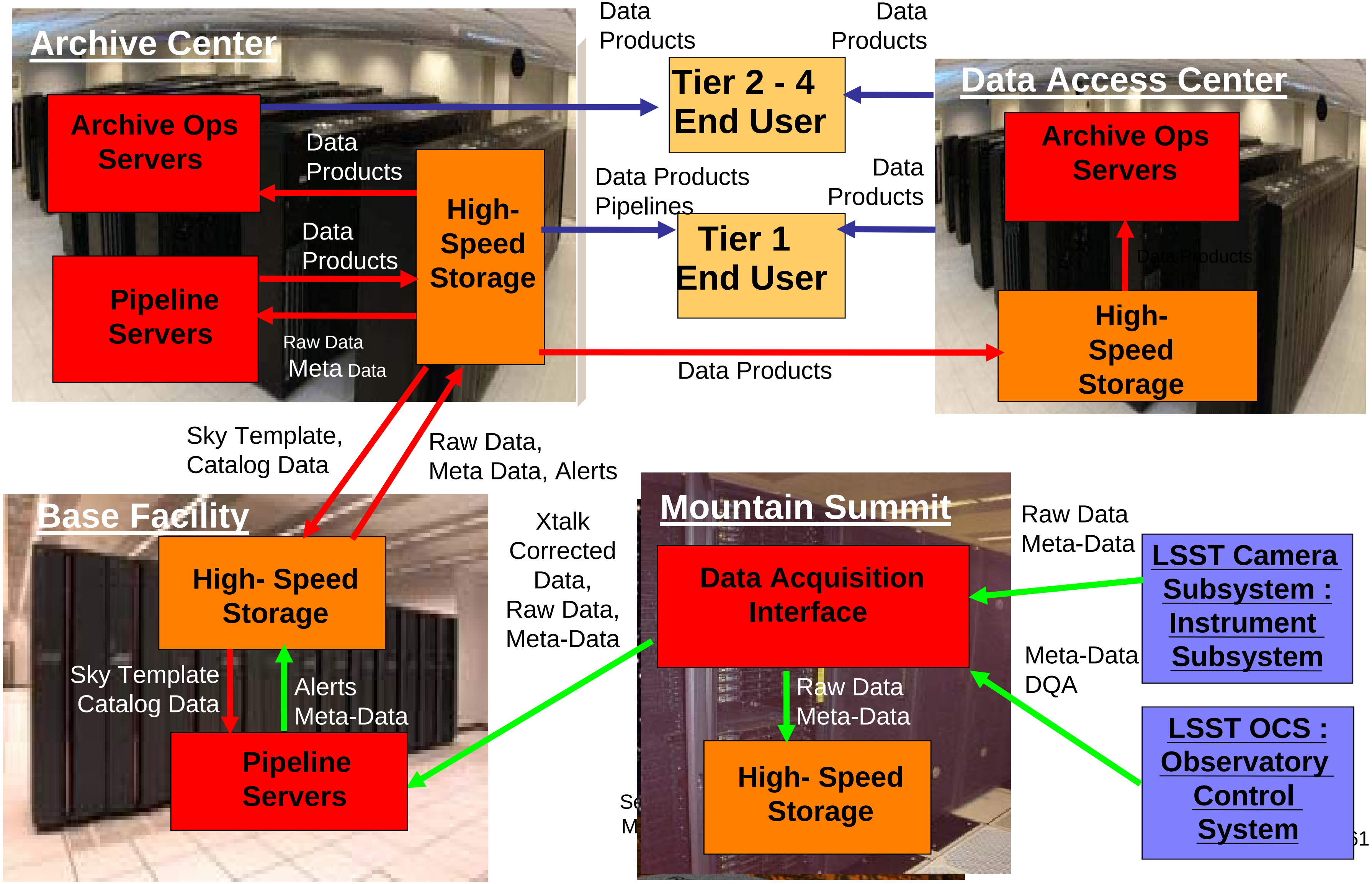
Infrastructure → Hardware
Computers, disks, data links, ,,,

Middleware → Interface wrapper
Device drivers, system management,…

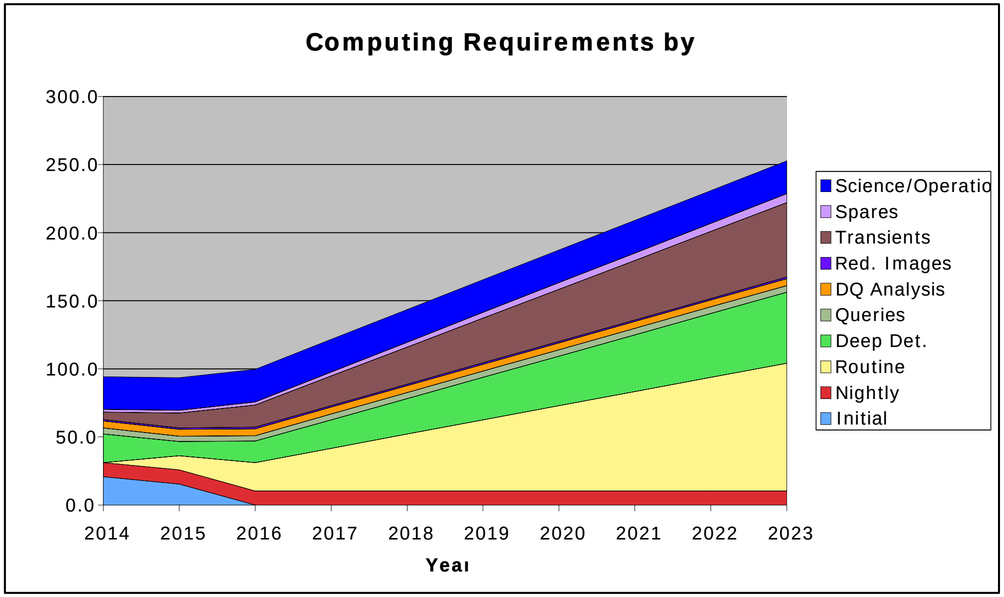
Applications → Science
Image processing, database queries, …

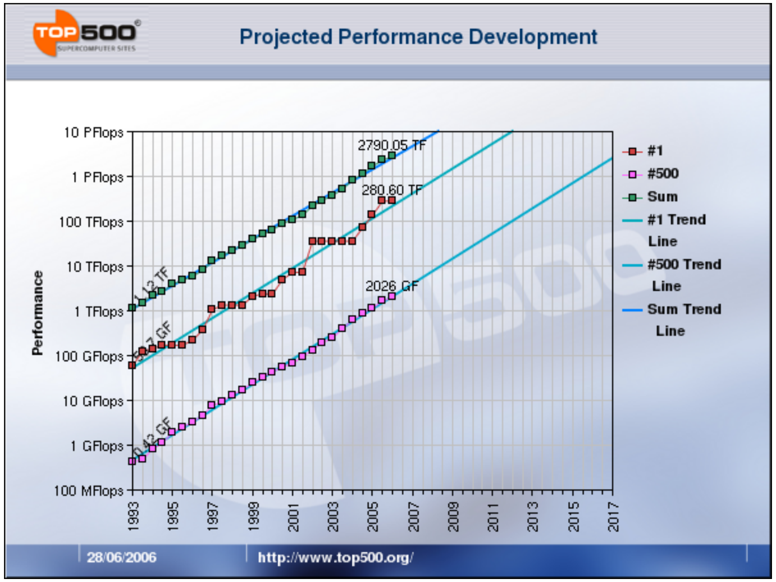
DMS Infrastructure is distributed and specialized to balance between real-time and non-real-time requirements

Large Synoptic Survey Telescope

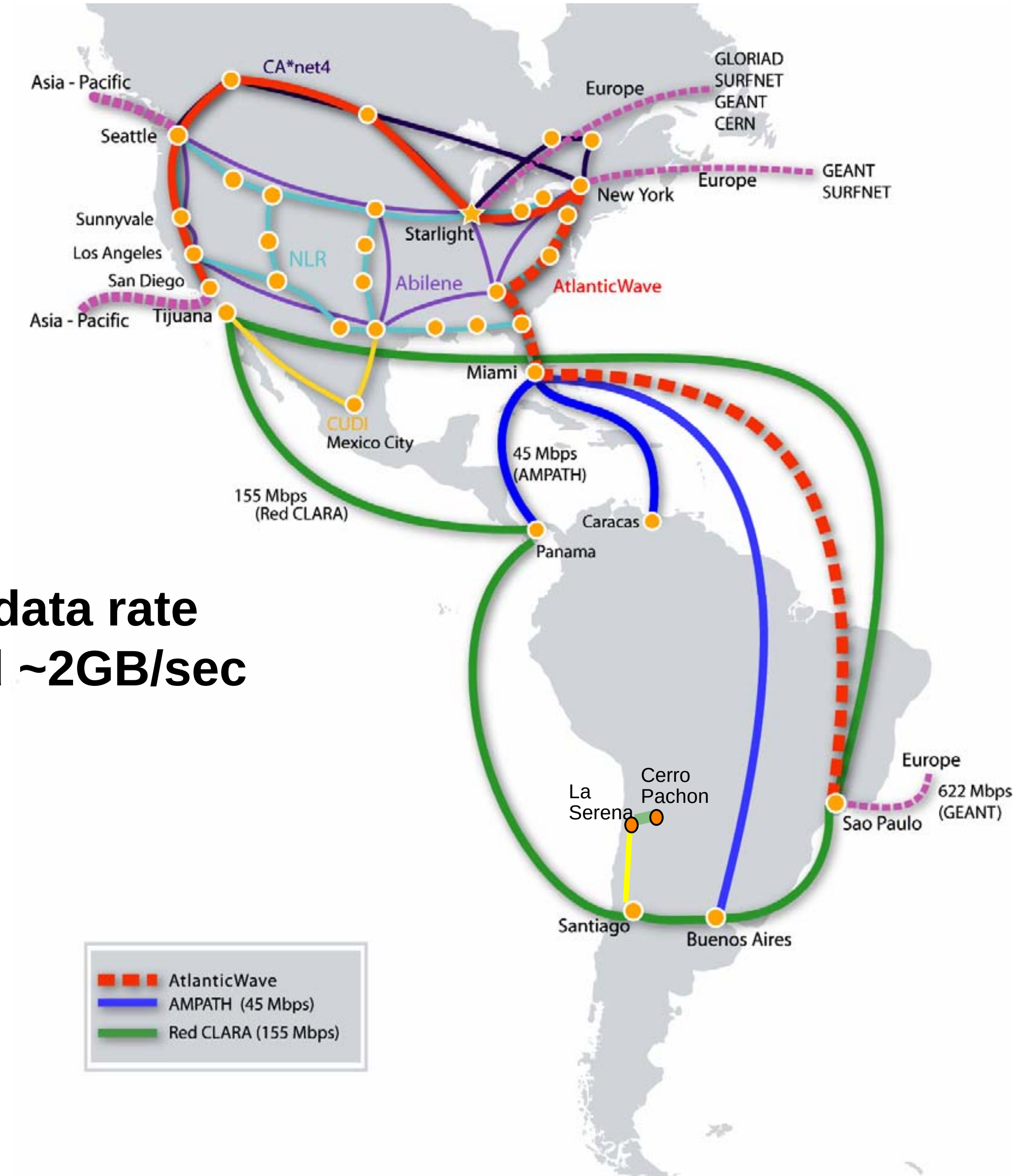


Computing Requirements



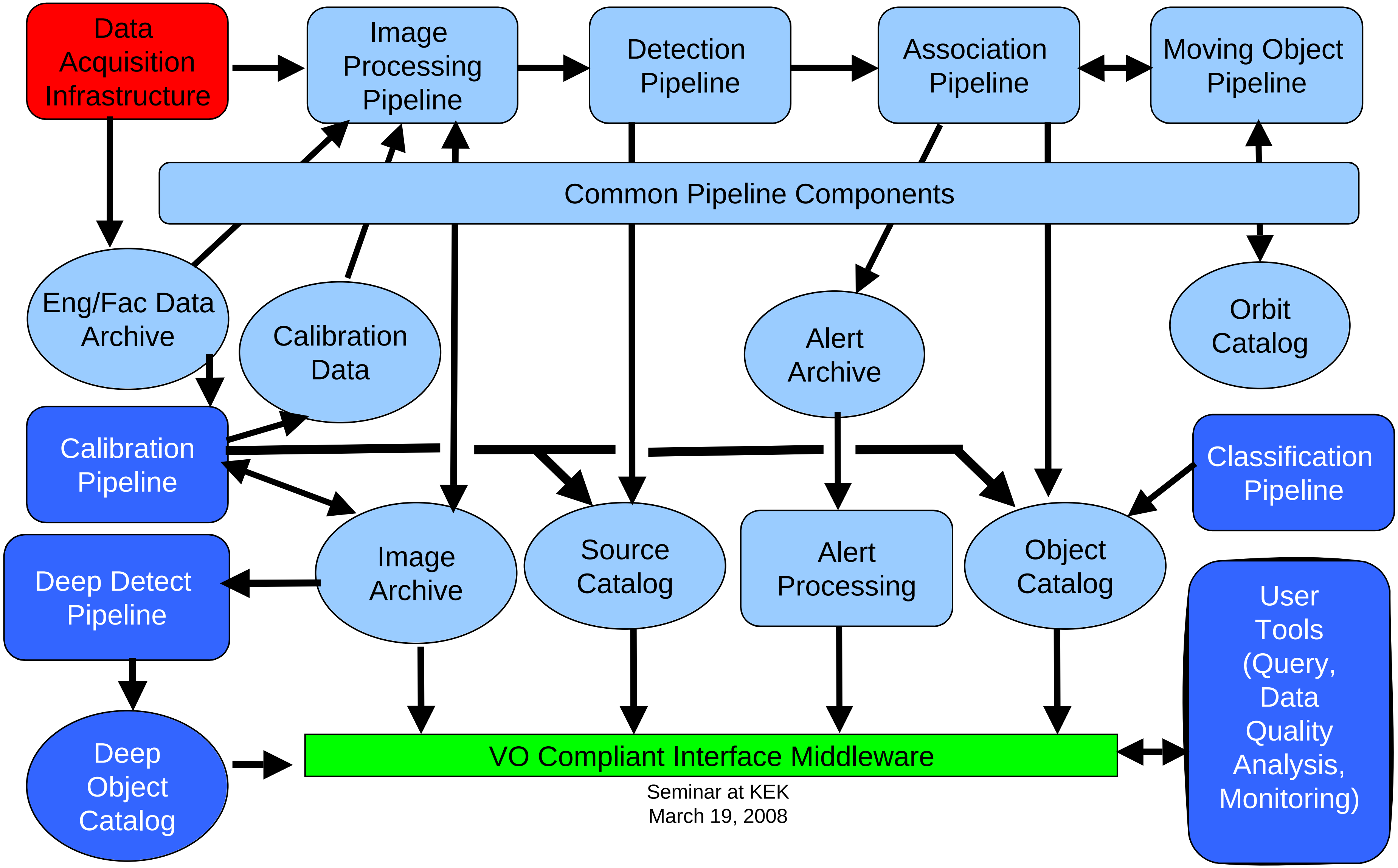


LSST will use existing NSF-funded fiber optic networks

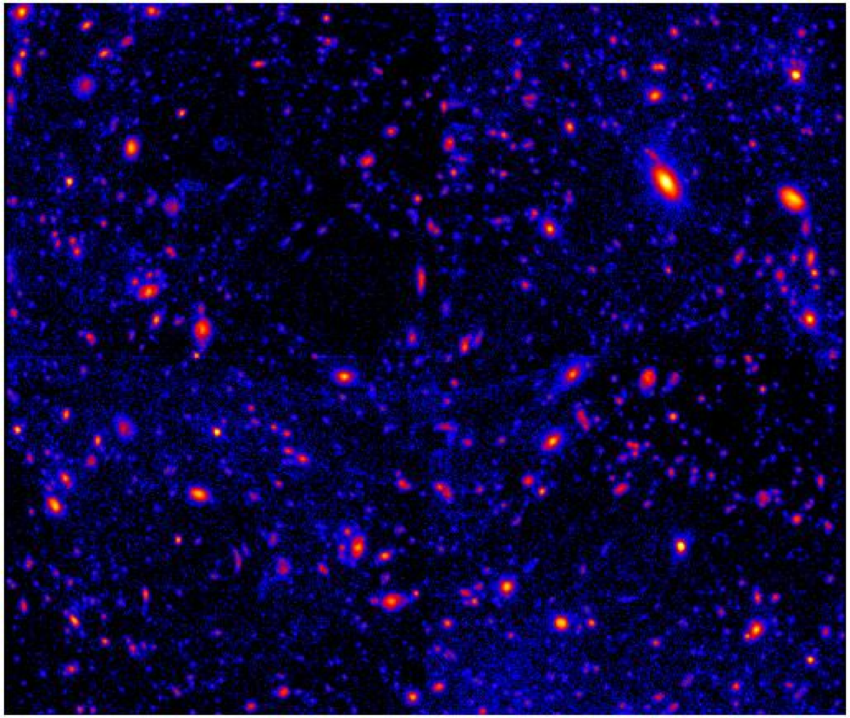


Typical data rate required ~2GB/sec

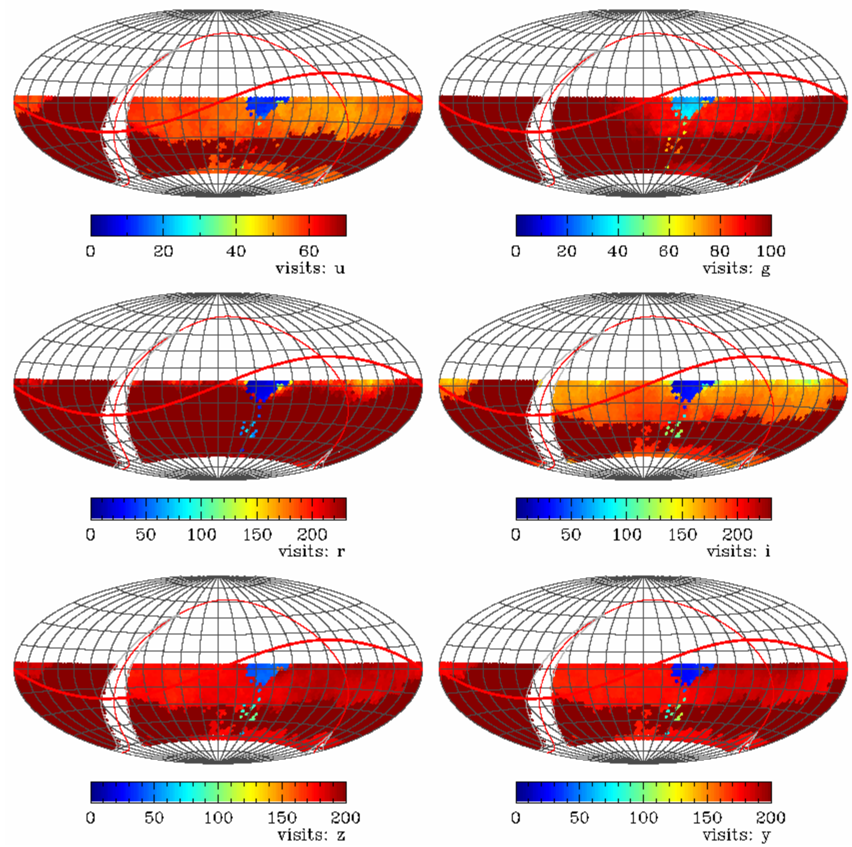
The Application Layer is composed of “real-time” and slower cadence parts



LSST imaging & operations simulations



Sheared HDF raytraced + perturbation + atmosphere + wind + optics + pixel



LSST Operations, including real weather data: coverage + depth

Project Schedule

- Reference Design complete
- Full WBS with dictionary and task breakdown
- Task-based estimate complete
- Integrated cost/schedule complete
- NSF MREFC proposal submitted February 2007
- NSF Concept Design Review held in September 2007
  - Project recommended for advancement to PDR
- DOE CD-1 review requested for Fall 2008
- NSF plans to advance the project to the National Science Board in Spring 2009
- Planning for FY2011 construction start, leading to “first light” in March 2015

Summary

- The LSST will be a world-leading facility for astronomy and cosmology. A single database will enable a large array of diverse scientific investigations. The project has broad support in the astronomy community, and it is therefore a key component of NSF's long-term plan for the field.

- LSST will measure properties of dark energy via weak lensing, baryon oscillations, Type 1a supernovae, and measurements of clusters of galaxies. It will test models of dark matter through strong lensing. No other existing or proposed ground-based facility has comparable scientific reach.

- The synergy in technical and scientific expertise between the astronomy and HEP communities will be essential to the project's success.

- A detailed initial design is in place for all major components of the system. With appropriate funding from NSF and DOE, the project is on-track to achieve first light in March 2015.